A model of information processing and interactions in teams developing technical systems

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ABSTRACT

Teamwork is often regarded as a critical operation element of product development organisations, whereas an efficient team-based approach to engineering design activities is a prerequisite for the success of technical systems development projects. Design team members thus need assistance in the form of methods and tools that will facilitate collaboration during team design activities, inasmuch as researchers and project managers require support in developing and prescribing the most appropriate and efficient methods and tools for the particular design tasks.

The research reported in the thesis aims at improving the understanding of designing in teams, primarily in the stage of conceptual design and from the perspective of information processing. A more specific research aim has been formed as follows: to review, develop and test models of team design activity in the development of technical systems, which will build on information processing and interactions appearing in team design activities in the conceptual design stage of the development. The main purpose of these models is to enhance decision-making and planning of technical systems development, by enabling both capturing and generating data sets that reflect process patterns distinctive for specific team compositions and working processes.

A state-transition-based theoretical and mathematical models have been developed and used to experimentally investigate the patterns of design operations performed during two types of team conceptual design activities – ideation and concept review – as well as two types of engineering design projects – adaptive and innovative. The presented work builds on the perception of design problems as ill-defined and implies that conceptual design activities involve the simultaneous development of problems and solutions through the usage of three distinctive design operations: analysis, synthesis, and evaluation. The three design operations have been defined as fine-grain design information-processing acts performed by design teams when exploring the content of both the problem space and the solution space. Moreover, design operations have been conceptualised as transitions between states of the explored design space, thus providing a basis for the state-transition model.

The developed models and the accompanying computational tool fulfilled the purpose of supporting research activity. The results of the protocol analysis and computational simulation studies indicate that the model can be used to identify, analyse and simulate sequences of design operations which are distinctive for specific working processes, such as divergent and convergent team conceptual design activities, as well as for a systematic approach to conceptual design. The experimental findings which could have been compared to the insight from the available literature have been found aligned with the current understanding of designing in teams. Based on the listed findings, it can be argued that the developed state-transition model provides more flexibility when it comes to capturing and comparing the patterns of analysis, synthesis and evaluation design operations in the problem and the solution space and offers the potential of improving design process understanding through either protocol analysis or computational studies of team conceptual design activity.

Keywords:

Engineering design process; Teamwork; Information processing; Technical systems development; Conceptual design; State-transition model; Ideation activity; Concept review activity

PROŠIRENI SAŽETAK

Timski rad ključan je element djelovanja gotovo svake organizacije, a učinkovit timski pristup razvojnim aktivnostima jedan je od preduvjeta za uspjeh inovativnih razvojnih projekata. Inovacije nisu specifično vezane samo za izvanredne pojedince već su i doprinos svih ljudi u organizaciji i njihovih zajedničkih aktivnosti. To su potvrdila i istraživanja posvećena formalnim procesima razvoja i nastanka inovacija te njihovom doprinosu uspješnom razvoju novih proizvoda, gdje su proučavanjem najboljih primjera iz prakse definirane smjernice koje je potrebno uključiti u razvojne procese organizacije kako bi se potaknula inovativnost. Uz to, u literaturi je primjetan značajan porast interesa za proučavanje ponašanja inženjera u postojećim procesima i timskim aktivnostima kao što su generiranje ideja, donošenje odluka, rješavanje problema ili pregled konstrukcije.

Istraživanja također pokazuju da još uvijek postoji potreba da se članovima razvojnih timova osigura bolja metodološka podrška i podrška u alatima za koncipiranje i konstruiranje tijekom timskih aktivnosti razvoja tehničkih sustava, a voditeljima projekata alati i metode uz pomoć kojih će se lakše nositi s izazovima koji proizlaze iz kompleksnosti upravljanja timskim radom. Kako bi se to omogućilo, potrebno je razviti formalne modele obrade informacija i interakcija za uobičajene timske aktivnosti u kontekstu razvoja tehničkih sustava. Implementacijom takvih modela u simulacijama timskog rada moguće je generirati skupove podataka potrebne za analizu utjecaja promjena u kompoziciji timova i načinu izvođenja radnih procesa, kao i donošenja odluka pri realizaciji razvojnih projekata.

Cilj je istraživanja osmisliti, formulirati i testirati teoretske i matematičke modele aktivnosti timskog rada u razvoju tehničkih sustava. Istraživanjem se modeliraju procesi obrade informacija i interakcije tijekom timskih aktivnosti. Svrha modela i njihove primjene u eksperimentalnim studijama jest prikupljanje i generiranje skupova podataka relevantnih za analizu obrazaca obrade informacija za različite kompozicije timova i različite radne procese, a koji se mogu koristiti za donošenje odluka pri planiranju i upravljanju razvojnim projektima.

Predloženim istraživanjem verificira se hipoteza da modeliranje i simulacija obrade informacija i interakcija pojedinaca koji sudjeluju u izvođenju timskih aktivnosti omogućuje razumijevanje značajki inovativnih i adaptivnih projekata razvoja tehničkih sustava te time unaprjeđuje planiranje i upravljanje razvojnim projektima.

Metodologija

Istraživanje je metodološki utemeljeno na općoj metodologiji istraživanja u znanosti o konstruiranju te je provedeno u četiri osnovna koraka: preliminarno istraživanje (raščišćavanje zahtjeva na istraživanje), pregled literature (deskriptivno istraživanje I), razvoj teoretskog i matematičkog modela (preskriptivno istraživanje) te provedba eksperimentalnih studija i validacije modela (deskriptivno istraživanje II). Preliminarno istraživanje uključuje pregled postojeće znanstvene i stručne literature unutar područja istraživanja s ciljem inicijalnog opisa postojeće situacije, željenih rezultata te definiranja osnovnih pretpostavki. Definirani su ciljevi, hipoteza i doprinosi istraživanja. Pregledom literature dan je uvid u vrste postojećih modela razvojnih procesa, s posebnim naglaskom na aspekte dekompozicije, obrade informacija i vrste razvojnih projekata. Pregled je uključio modele različitih razina granuliranosti, od modela koji opisuju faze razvoja novih proizvoda do modela timskih aktivnosti koji opisuju korake obrade informacija i interakciju članova tima. Ishod toga koraka jest formulacija istraživačkih pitanja, čime je usmjeren daljnji tijek istraživanja. Razvijena su dva modela. Teoretski model kao dio teoretskog okvira razvijen je na temelju saznanja iz pregleda literature. Drugi, matematički model kreiran je na temelju statističke analize podataka prikupljenih prvom eksperimentalnom studijom. Uz modele su razvijene pripadajuće vizualizacije procesa obrade informacija te računalni alat za simulaciju procesa koncipiranja proizvoda. Eksperimentalne studije provedene su primjenom razvijenih modela u svrhu analize i generiranja podataka relevantnih za procesuiranje informacija u timskim aktivnostima razvoja tehničkih sustava. Rasprava o rezultatima eksperimentalnih studija ujedno je i evaluacija razvijenih modela, posebice u odnosu na formulirana istraživačka pitanja te prema kriterijima postavljenih ciljeva i hipoteze istraživanja.

Teoretske osnove

Preliminarnim pregledom literature istraživanje je fokusirano fazu koncipiranja proizvoda, gdje se tijekom razvoja tehničkih sustava javlja velika potreba za timskim radom. Za dekompoziciju i modeliranje procesa obrade informacija odabrana je paradigma operacija konstruiranja. Operacije konstruiranja osnovni su mehanizmi obrade informacija kojima se članovi tima koriste kako bi manipulirali sadržaj dviju dimenzija prostora konstruiranja – prostora problema i prostora rješenja.

Formulirane su definicije triju temeljnih operacija, odnosno skupina operacija obrade informacija u kontekstu timskog koncipiranja proizvoda: analize, sinteze i evaluacije. Timovi analiziraju kako bi unaprijedili razumijevanje pojedinih konstrukcijskih entiteta u istraženom prostoru konstruiranja. Analizom prostora problema raste razumijevanje potreba, zahtjeva i ograničenja dok se analizom prostora rješenja povećava razumijevanje ideja, koncepata i koncepcijskih alternativa. Nadalje, timovi sintetiziraju kako bi stvorili nove entitete u prostoru konstruiranja. Sintezom rješenja nastaju novi entiteti, ideje i rješenja za zadane probleme dok sintezom problema nastaju entiteti koji opisuju nove potrebe, zahtjeve i ograničenja. Naposljetku, evaluacijom se ocjenjuje korisnost pojedinih entiteta u istraženom prostoru konstruiranja. Za razliku od analize i sinteze, evaluacija uključuje i entitet kriterija u odnosu na koji se provodi ocjenjivanje.

Tri temeljne operacije u prostoru konstruiranja objedinjene su u teoretski model prijelaza stanja, kao tranzicije između stanja razvijanog tehničkog sustava, odnosno stanja procesa konstruiranja. Tako koncipiran model omogućuje preslikavanje i analizu udjela operacija konstruiranja, njihovih sekvenci i vjerojatnosti prijelaza iz jedne operacije u drugu tijekom timskih razvojnih aktivnosti. Uz model prijelaza stanja razvijene su i pripadajuće vizualizacije udjela operacija konstruiranja te su definirane varijable i mjere za analizu procesa pomoću eksperimentalnih studija.

Eksperimentalna studija analize protokola

Testiranje teoretskog modela i pripadajućih vizualizacija provedeno je eksperimentalnim studijama. Prva studija provedena je korištenjem analize protokola, a s ciljem identifikacije obrazaca analize, sinteze i evaluacije u prostoru problema i rješenja za dvije različite vrste timskih aktivnosti u konceptualnoj fazi razvoja tehničkih sustava – generiranja ideja i pregleda koncepata. Analiza protokola provedena je za četiri razvojna tima sastavljenih od studenata viših godina strojarstva. Svaki je tim sudjelovao u jednoj aktivnosti generiranja ideja i jednoj aktivnosti pregleda razvijenih koncepata. Proces obrade informacija analiziran je metrikama i vizualizacijama predloženim u okviru teoretskih osnova modela prijelaza stanja.

Primjena teoretskog modela omogućila je identifikaciju obrazaca obrade informacija i interakcija karakterističnih za dvije analizirane aktivnosti, poput divergentnih ciklusa sinteze problema i rješenja tijekom aktivnosti generiranja ideja ili konvergentnih ciklusa analize i evaluacije rješenja za vrijeme aktivnosti pregleda koncepata. Nadalje, primjena modela omogućila je identifikaciju obrazaca koji su bili učestali u obje aktivnosti, poput obrazaca sekvenci operacija analize, sinteze i evaluacije rješenja te primjene sinteze kao sredstva za prebacivanje iz prostora problema u prostor rješenja i obratno. Potvrđeno je da se odmicanjem faze koncipiranja smanjuje udio operacija konstruiranja u prostoru problema.

Rezultati prve eksperimentalne studije također otkrivaju da timovi na sličan način pristupaju istraživanju prostora problema i rješenja, koristeći se sličnim sekvencama analize, sinteze i evaluacije. Posebno je zanimljivo da ni aktivnost generiranja ideja ni aktivnost pregleda koncepata ne održavaju mikroobrasce sekvenci operacija konstruiranja kao što su analiza – sinteza – evaluacija ili sinteza – analiza – evaluacija, na kojima se temelje neki od modela aktivnosti konstruiranja razmatranih pregledom literature.

Matematički model i računalne eksperimentalne studije

Rezultati i saznanja o obrascima obrade informacija iz prve eksperimentalne studije iskorišteni su za razvoj matematičkog modela. Identificirane su i statistički modelirane veze između udjela i sekvenci operacija konstruiranja. Te su veze, vodeći računa o teoretskim osnovama prijelaza stanja, objedinjene i formalizirane unutar matematičkog modela. Validacija matematičkog modela provedena je repliciranjem rezultata prve eksperimentalne studije (analize protokola). Matematički je model zatim računalno implementiran simulatorom aktivnosti obrade informacija i interakcija u konceptualnoj fazi razvoja tehničkih sustava te su razvijeni novi eksperimenti s ciljem istraživanja obrazaca obrade informacija u inovativnim i adaptivnim razvojnim projektima. Postavke simulacija inovativnih i adaptivnih projekata definirane su na temelju saznanja proizašlih iz pregleda literature.

Niz simulacija adaptivnih i inovativnih projekata omogućio je prikupljanje veće količine podataka o udjelima, redoslijedu i vjerojatnostima primjene operacija konstruiranja u različitim stadijima koncipiranja tehničkih sustava. Identificirani su prijelazi stanja karakteristični za dvije vrste projekata, poput konvergentnih ciklusa analize i evaluacije te divergentnih ciklusa sinteze i evaluacije unutar i između prostora problema i rješenja. Nadalje, takvi se prijelazi stanja mogu direktno povezati s koevolucijom prostora problema i rješenja, odnosno epizodama u procesu gdje istraživanje jedne dimenzije prostora konstruiranja izaziva stvaranje novih entiteta u drugoj dimenziji. Više potencijalnih epizoda koevolucije identificirano je za inovativne projekte. S druge strane, u simulacijama procesa adaptivnih projekata uočena je viša razina sistematičnosti, ponajviše u obliku dobro uočljivih konvergentnih i divergentnih stadija konceptualne faze. Formulirana je tvrdnja da su sistematičnost i epizode koevolucije usko povezani s dekompozicijom zadanog konstrukcijskog problema u potprobleme, ali i s neizvjesnošću u planiranju sljedećih koraka procesa razvoja. Adaptivne projekte karakteriziraju niža razina neizvjesnosti i eksplicitna dekompozicija problema na početku konceptualne faze, a inovativne projekte visoka razina neizvjesnosti i implicitna dekompozicija problema.

Vrednovanje istraživanja

Vrednovanje teoretskog i matematičkog modela, kao i podataka prikupljenih analizom protokola i računalnim simulacijama provedeno je raspravom kojom se adresiraju hipoteza, ciljevi i istraživačka pitanja. Rasprava se također oslanja na saznanja iz dostupne literature.

Razvijeni teoretski i računalni modeli te popratne vizualizacije ispunili su svrhu podrške istraživanju timskih aktivnosti u razvoju tehničkih sustava. Rezultati eksperimentalnih studija ukazuju da se modeli mogu koristiti za identifikaciju, analizu i simulaciju obrazaca operacija konstruiranja, poput sekvenci analize, sinteze i evaluacije u prostorima problema i rješenja, a koji su karakteristični za različite razvojne procese, poput divergentnih i konvergentnih timskih aktivnosti te sistematičnog pristupa konceptualnoj fazi razvoja tehničkih sustava. Rezultati analize protokola i računalnih simulacija u skladu su s trenutnim saznanjima u području znanosti o konstruiranju. Štoviše, u usporedbi s postojećim modelima, razvijeni teoretski i matematički modeli, koji se koriste paradigmom prijelaza stanja, nude veću fleksibilnost proučavanja i opisivanja obrazaca operacija konstruiranja i time unaprjeđuju razumijevanje timskog konstruiranja.

Razvijene vizualizacije prijelaza stanja na tri načina dodatno proširuju razumijevanje identificiranih obrazaca. Prvo, kao svojevrsni sažetak svih prijelaza između operacija konstruiranja unutar i između prostora problema i prostora rješenja, koji odražava frekventnost prijelaza iz jedne operacije konstruiranja u drugu. Drugo, vizualizacije se mogu koristiti kao predlošci za zapisivanje i prikaz učestalih obrazaca sekvenci operacija konstruiranja, ali i obrazaca koji su specifični za pojedine timske aktivnosti u konceptualnoj fazi razvoja tehničkih sustava. Treće, vizualizacije promjene udjela pojedinih operacija konstruiranja tijekom timskih aktivnosti omogućuju intuitivnu analizu, usporedbu i karakterizaciju procesa konstruiranja za različite timove te mogu pomoći u analizi pojava poput iteracije, neizvjesnosti, istraživanja prostora konstruiranja i sistematičnog pristupa konstruiranju.

Na temelju vrednovanja istraživanja naglašena su tri osnovna aspekta znanstvenog doprinosa. Prvi aspekt obuhvaća razvoj teoretskog modela procesa obrade informacija te interakcija između pojedinaca u timskim aktivnostima razvoja tehničkih sustava te niz novih saznanja o timskim aktivnostima dobivenih primjenom teoretskog modela i paradigme prijelaza stanja za analizu protokola aktivnosti generiranja ideja i pregleda koncepata. Drugi aspekt uključuje pripadajuće originalne načine vizualizacije udjela i uzoraka tranzicija među analizom, sintezom i evaluacijom u prostoru problema i rješenja za timske aktivnosti u razvoju proizvoda. Treći aspekt znanstvenog doprinosa obuhvaća razvoj matematičkog modela i računalnog alata za simulaciju timskih aktivnosti temeljem predloženog teoretskog modela, u svrhu boljeg razumijevanja, planiranja i upravljanja razvojnim projektima, kao i stvaranja novih saznanja o timskom radu u konceptualnoj fazi adaptivnih i inovativnih projekata razvoja tehničkih sustava.

Ključne riječi:

proces konstruiranja; timski rad; obrada informacija; razvoj tehničkih sustava; koncipiranje; model prijelaza stanja; aktivnost generiranja ideja; aktivnost pregleda koncepata

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AI	-	Artificial Intelligence
ASE	-	Analysis, Synthesis and Evaluation
BAH	-	Booz Allen Hamilton
C-K	-	Concept-Knowledge
DDP	-	Design and Development Process
DfX	-	Design for X (Design for Excellence)
DRM	-	Design Research Methodology
EDR	-	Experimental Design Research
FBS	-	Function-Behaviour-Structure
IMoD	-	Integrated Model of Designing
IPD	-	Integrated Product Development
IPS	-	Information Processing System
NPD	-	New Product Development
O	-	Other (protocol code not related to design process)
PA	-	Problem analysis design operation
PDMA	-	Product Development and Management Association
PE	-	Problem evaluation design operation
PRO	-	Problem-related design operation
PROC	-	Process-related protocol code
PS	-	Problem synthesis design operation
R&D	-	Research and Development
SA	-	Solution analysis design operation
SE	-	Solution evaluation design operation
SOL	-	Solution-related design operation
SS	-	Solution synthesis design operation

Symbols

n	-	Total number of design operation instances in a protocol string
n_i	-	Number of instances of design operation *i*
p_i	-	Proportion of design operation *i*
R	-	Maximum vector length in ASE proportion visualisation
r	-	Vector length in ASE proportion visualisation
δ	-	Vector direction angle in ASE proportion visualisation
κ_a	-	Event alignment kappa value

1. INTRODUCTION

This introductory chapter outlines the research goal and clarifies its scope in the context of engineering design research. The reader is introduced with the motivation for investigating team design activity and is provided with a brief overview of the aims, hypothesis, methodologies and the expected contribution driving the work reported in the thesis.

Innovative product development is a critical activity of contemporary product development organisations [1], [2]. Although both the older [3] and the more recent [4] studies have pointed out different types of innovation and different meanings it can have to the stakeholders involved, it is generally agreed that development organisations cannot realise or retain long-term global competitiveness without successfully and repetitively introducing new and innovative products. Over the years, the research efforts (reported mainly within the domain of management research) attempted to identify critical success factors in product development and provided numerous best practice guidelines based on studies of highly innovative organisations across the industries (see, e.g. [5], [6], [7], [8], [9] for more details on the new product development (NPD) best practice studies). Among other things, the studies have broken a common misconception that innovativeness is specifically related only to exceptional individuals, and revealed that, in the ever increasing competitive and interdisciplinary environment, innovation is primarily a contribution of groups of people within the organisation and a result of their joint activity [10], [11] – teams and teamwork [12].

Within the domain of engineering design, which is at the very core of technical systems development, team collaboration turned up to be essential when no single actor has all the time, knowledge, skills or inspiration needed to realise a particular design task [13], [14], [15]. In addition, teamwork has provided many advantages over individual work and has been related to different desirable outcomes such as improved problem solving and product quality, and the reduction of development time and costs [16], [17]. Consequently, being able to work in a team is perceived as one of the core design competencies [18], whereas the engineering design education increasingly encompasses skills such as communication and teamwork, in order to prepare design students for the creative design tasks that emerge in the real-world, professional product development context [19], [20], [21].

Due to the initial individualistic focus of design research, most of what has been known about the engineering design process has resulted from studies of individual designers [22]. Although the number of studies aimed at understanding designing in teams is continuously increasing [23], their proportion remains marginal when compared to studies that examine designing with an individualistic focus [24]. While team design activities are potentially the most creative, vibrant and dynamic from the designers' point of view [25], there still remain aspects of team designing that are less understood by the researchers (see, e.g. the research questions formulated in Chapter 2), thus leaving open calls for both theoretical and experimental research that could frame the comprehensive understanding of teamwork in design.

Therefore, the motivation for conducting the presented research stems primarily from the need for developing, adapting and upgrading the design process models for studying team design activities, thus providing a foundation for building a better understanding of teamwork in engineering design. The motivation founds primarily on a presumption that there exist regularities in designing that transcend any individuals involved in the process [26], [27]. As shown hereafter, the potential benefits of modelling the "designerly" behaviour in team design activity are, at least, twofold.

Firstly, a better understanding is seen as a prerequisite for the development of **better methodological and computational support for design teamwork**. Namely, given that the fundamental goal of design research is often expressed as improving the design in practice, it is not surprising that its efforts resulted predominantly in an exceedingly large amount of different design methods and tools, rather than providing better understanding and comprehensive models of design [28]. For example, while the efforts of computer-supported collaborative environments could have indeed facilitated design teamwork [29], most of the developed means of support remained at a theoretical level, whereas only a few were implemented in practice [30]. The lack of adequate computational support tools in design practice has been particularly evident in the conceptual design stage of product development [31], [32], [33], during the critical activities such as ideation [34] and design review [35]. Moreover, the tools for collaborative design may fail in supporting effective communication of ideas and information, primarily due to the insufficient exploration of information flows in design teams [15]. It is agreed that the development of support that is intended to improve the design process is likely to be far more efficient and effective if different aspects of designing are better understood [30], [36]. Proper models of the actual design processes have thus become essential for understanding designers' information processing and interaction, as well as developing tools that could assist collaborative designing [15], [28], specifically, design teams in formulating design problems and providing solutions to these problems.

Secondly, an eventual sufficient understanding of interactions and information processing in engineering design teams is expected to **facilitate design team formation and management**. Since teams in product development are usually project-based [11], it is not uncommon for members of design teams to meet for the first time at the start of a project [37] and produce one-time outputs only [38]. Design teams are formed by project managers and can drag members from different disciplines, based on their expertise and ability to contribute to a particular project, whereas some members work on the project until it is completed, and some join for shorter periods [38]. It is thus argued that a better understanding of the effects of design team composition on the design process and design outcomes facilitates the construction and management of effective teams [39]. However, when it comes to forming project-based teams, many selection strategies may assist, but none has emerged as a consistent predictor of effectiveness [40].

For this reason, team formation represents a significant challenge for project managers, as they try to select optimal team memberships and distribute the work activities. Depending on the product's novelty level (often described using terms categorised as original/innovative, adaptive/redesign, variant/configuration, and incremental/routine) [41], [42], different types of design work are expected to be in team's focus [43]. Thus, traditional engineering design might require engineers to solve complex engineering problems with specifications already set and baseline product predetermined [44], while the development of innovative consumer products requires precise identification of users' needs [45]. The understanding of team information processing and gaining insight into actions and interactions in project-based design teams facing different types of product development projects is thus important for both researchers and practitioners within the domains of product design and development.

The ability to combine experimental research on the nature of team information processing (e.g. [46], [47], [48]) with the advances in information technologies has opened a space for utilising computer-supported simulations of teamwork as complementary tools for research and management. Although mathematical and computational modelling are currently not fully exploited for design process simulation, they exhibit a high potential for the investigation of fine-grain models of engineering design activity [49]. In this way, the two outlined benefits would intertwine, given that the better understanding of team information processing and interaction helps design researchers not only to better support design teamwork but also to conduct analyses of various design process scenarios, whose insights can then be employed by project managers when forming design teams or allocating resources.

1.1. Research focus, aim and hypothesis

The acts related to designing represent a set of complex, multi-layered phenomena [30], [50], [51], while the organisations that undertake designing (e.g. product development firms) can be seen as complex socio-technical systems [52]. Therefore, any study of teamwork in design must acknowledge that because of the large number of variables involved and due to the multifaceted nature of the design process [46], [53], only some aspects of designing can be addressed at a time. For example, recent studies in the engineering design domain have investigated team design processes through the lenses of design thinking and cognition [54], [55], [56], [57], communication [58], [59], [60], creativity [61], [62], learning [13], [63], [64], systematic approaches to solving a problem [65], [66] as opposed to the co-evolutionary design progression [67], and more. Additionally, insights on human behaviour from domains such as psychology, management and education, are continuously being incorporated in order to yield the most relevant results. Ideally, studies of different aspects of teamwork (within and outside the engineering design domain) should, in the manner of a jigsaw puzzle, be compatible and provide knowledge fragments needed for a comprehensive description of team design activities.

The phenomenon of interest in this thesis is the observable information processing performed by the members of a design team, whereas the aspects such as cognition, learning, creativity and personal characteristics of team members are not directly in focus. Information processing is here interpreted as a process-oriented paradigm [68], which accounts for any manipulation of the design content (design information) aimed at providing a solution to a particular design problem. Such highly abstract interpretation aligns with the definitions of engineering design that focus on information and its conversion or transformation [69], [70], e.g. *“Engineering design is a process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that technical systems meet the needs of mankind”* [71] or *“Engineering design is the process of converting an idea or market need into the detailed information from which a product or technical system can be produced”* [72]. Similar views on information processing can be applied to any type of problem-solving activity in general [41].

As it is the case with the design process, the investigation of team information processing (in its broadest sense) within the engineering design literature is variegated and depends highly on the addressed aspects of the design process. Thus, a more detailed overview and synthesis of research efforts related to design information processing is introduced later in the thesis.

Three main reasons for focusing primarily on the information processing phenomenon in order to describe the team design activity can be outlined:

- **Information processing is relevant as a theoretical lens for studying team design activity.** It has been argued that engineering design can be modelled as a series of information processing activities, where each step in the process involves design team identifying and obtaining information that defines a particular sub-problem and then use knowledge, skills and tools to transform the state of information into solutions or sub-solutions [73], [74], [75]. Hence, the execution of information processing acts, such as analysis, synthesis and evaluation of design information, can be seen as a dominant working mode of design teams throughout the design process [76], [77]. Given the previously introduced conjecture that there exist regularities in designing, the measuring of information processing is here proposed as a proxy for identifying such regularities. It is thus argued that if the regularities are captured within a model of information processing in design teamwork, that model can be used to describe other phenomena studied by the design research. For example, studies have shown information-processing patterns can reflect phenomena such as fixation, inspiration and creativity [78] or the difference between experts and novice designers [79], [80].
- **Methods for studying information processing reached maturity.** The claim applies particularly for the protocol analysis, a frequently employed process-oriented analysis method which is largely based on the information processing perspective of the design process [81]. Protocol studies have been conducted to gain an understanding of ways and approaches to designing, whereas the resulting protocols of the design process have been widely used to record designers' step-by-step information processing [82], [83]. Information processing paradigm and the verbal protocol analysis method pioneered by Ericsson and Simon [84], have been present within a vast number of engineering design studies for decades, and have as such developed scientific validity and maturity. Their establishment has also been supported by the ever-increasing capability, efficiency and affordability of data capturing and analysis tools needed to perform experimental studies of information processing in design (audio-video hardware and software) [85].
- **Information processing perspective is applicable to the development of computational design support tools.** Within the information processing paradigm, it is

assumed that human problem solver together with the task environment and the explored problem/solution space represent an information processing system (IPS) [77], [86]. Given the premise that IPS-like exploration of alternatives within the design space is a valid basis for a computer-based design support [87] and that such support must be integrated into the streams of information processing within the design process [82], it can be argued that an information processing model of design teamwork could provide a foundation for the development of computational tools that can support team design activity. Such argumentation for the compatibility of IPS theories and computational design support tools is already well accepted in design research. Namely, the models of information processing have been acknowledged to form a basis for the support of design practice, theory and education [88], as well as the simulation of design teamwork [89] and artificial intelligence (AI) driven designing [77], [90].

The observable information processing itself is a multi-layered phenomenon, consisting of both the verbal and the non-verbal acts. As shown later in the thesis, the research focus has been narrowed down primarily to the verbalised portion of the observable information processing. It is important to point out the limitations of such an approach, that is the drawbacks of neglecting the non-verbalised, as well as the non-observable aspects of the design process.

The non-verbalised (behavioural) acts, such as gestures, gaze/looking, posture, emotional states and sketching/drawing [91], [92], [93], although more challenging to identify and interpret, have proven to be valuable information-processing elements within the design process and can, as such, transform the meaning of verbalised words. For example, gestures are considered a prominent mode of both thinking [94] and communication in design teams [92], [95], whereas design representations have been found to influence idea generation and fixation in design [96]. The concurrent reporting ("think-aloud" verbalisation), which is often employed in experimental studies of design cognition, fails to grasp the whole thought process as soon as participants stop speaking or use mental images [97], [98]. Therefore, restricting the analysis solely to the verbally processed and communicated information comes at the cost of not being able to develop a complete depiction of design team information processing. Instead, the verbalised information processing can be perceived as a single layer which outlines and indicates the overall, multi-layered process. The quality of this outline depends on the interpretation of verbal information processing, which may be improved by taking into consideration gestures, sketches, and other observable aspects of the design process. Moreover, some of the critical limitations identified for concurrent reporting, such as the effects of verbalisation on the design process [98] or encouraging participants to change parallel tasks to serial [99], concern primarily the studies of individual designers. As such, these limitations of "thinking aloud" do not apply when studying team designing.

Additional limitations stem from focusing on observable information-processing acts only (e.g. by means of concurrent verbal protocol analysis), which leads to neglecting aspects such as perception and insight [23], the effects of experience, competences, knowledge and skills, as well as crucial information embedded within non-verbalised thoughts [100]. Also, studies producing observational data tend to be resource-intensive and often include smaller sample sizes [23], [99] and are thus subject to a high margin of uncertainty when it comes to statistically significant results [101]. At present, the study of observable information processing in design teams is constrained by its explorative and indicative nature.

Furthermore, due to the diversity of design tasks appearing within the engineering design process and many stages it iterates through [49], [102], it is difficult to isolate and model any one type of team design activity that would adequately summarise the full scope of teamwork in the development of technical systems. Therefore, the here presented work will focus mainly, but not exclusively, on team activities within the context of the conceptual design stage of technical systems development. The following rationale can be provided for such a narrowing:

- **Team design activities are conducted primarily during the conceptual design stage.** The potential for harnessing the advantages of team designing prevails mainly within the conceptual design stage of product development, where designers transform the initial and often ill-defined formulation of a design problem is into a clear description of a concept solution, thus ensuring a more certain design work in the subsequent stages [50], [103]. The conceptual design stage makes the greatest demands on designers and offers the most scope for striking improvements [104]. A teamwork approach to framing design problems and developing solutions to these problems is believed to be the driver of creativity and innovativeness in the early product development stages [67]. Hence, not only does the majority of engineering designers in modern industrial practice work as part of a team [105], [106] but the creative conceptual design tasks such as idea generation or concept selection, are often performed exclusively as team activities [61], [107]. It is thus not surprising that a large portion of experimental design research on team behaviour in last decades has been related directly to the conceptual design stage [23].
- **Conceptual design stage encompasses critical design information processing.** Although the early part of the design process is relatively inexpensive and involves

> relatively small groups of people, it incorporates handling of and communicating large amounts of information [32] and furthermost important [104], but often ad hoc decision-making [108], which together significantly impact the subsequent development stages. Most of the information communicated by designers during conceptual design is verbal [50], [109], occasionally backed up by visual representations as to facilitate shared understanding [110]. Such distinctive nature of information processing, which is specific for conceptualisation when compared to the later stages such as detailing and testing, contributes to the previously mentioned lack of adequate support for team conceptual design activities [31], [32], [33], [34], [35]. Hence, capturing and modelling of conceptual design information processing is argued to be a critical step towards developing of a better support of communication and decision-making in design teams.

Taking into account the information-processing perspective, and based on the outlined lack of understanding and support for team activities in engineering design (particularly within the conceptual design stage), the aims and hypothesis of the research can be summarised as follows:

Research aims: The principal aim of the research is to review, develop and test models of team design activity in the development of technical systems. Given the outlined research focus, the models will build on information processing and interactions of engineering designers during team design activities, particularly within the conceptual design stage of product development. The purpose of the developed models and their application in experimental studies of team designing is to enable both capturing and generation of data sets relevant for the analysis of design process patterns that are distinctive for different team compositions and working processes, thus enhancing decision-making in planning and management of development projects.

Hypothesis: The proposed research will verify the hypothesis that the modelling and simulation of information processing and interactions of individuals that perform teamwork activities enable understanding of the features of innovative and adaptive technical systems development and thus facilitate research, planning and management of development projects.

1.2. Research methodology

In general, the aim of research in engineering design science is to formulate and evaluate models and theories on the phenomenon of design and development of technical systems, based on which the strategies, procedures, methods, techniques and tools can be developed to improve theoretical and practical knowledge, project management and education [30]. Developing models of designing is a complex task that requires integration of multiple approaches and disciplines [111], particularly regarding engineering design and management research. Two ends of the spectrum of design research knowledge can be highlighted: practical and theoretical knowledge [112]. Methodologically, the two corresponding strands of design research usually result in the development of understanding (typically the descriptive approaches) and the development of support (prescriptive approaches) [30]. Yet both the understanding (descriptive) and the support (prescriptive) are needed to make the design process more effective and efficient.

The appropriate interplay between prescriptive and descriptive approaches needed for conducting the here presented research has been found within the Design Research Methodology (DRM) [30] – a general and increasingly spread research methodology in design science. Moreover, as shown hereafter, the research has also been guided by the principles of Experimental Design Research (EDR) [113] and the Principles for the Construction of Design Science [70].

Although the presentation of the research methodology stages is sequential, the conducted work has required iterative execution of research steps. This iterative nature is particularly evident in the case of model development and evaluation, where the models are developed and experimentally evaluated in a series of prescriptive and descriptive steps. As such, this particular research project and its main focus can be described as that of Type 4 in DRM [30]. The Type 4 DRM research project is characterised by the literature review-based Research Clarification and Descriptive Study I stages, followed by a review-based support development and evaluation (first cycle of Prescriptive Study and Descriptive Study II stages), before finally the initial or comprehensive support is developed and evaluated (second cycle of Prescriptive Study and Descriptive Study II stages), as shown in Figure 1.1. The resulting research methodology consists of four main steps, which can be described as follows:

1) **Research clarification:** This step fully corresponds to the first stage of the DRM methodology. Here, the needs for conducting the (research) work must have been identified and well interpreted. The clarification includes forming the line of argumentation from the existing situation in the field of research to the research goal [30] (as presented so far in this introductory chapter). The stage resulted in an overall research plan which contains the description of the research problem, the focus, aims and hypothesis, research scope and relevant research areas to be reviewed, the research

methodology, the expected contribution and the schedule. The research plan implies also the embracement of acknowledged scientific principles and methods [70].

2) **Literature review:** Once the research scope has been clearly defined, it was possible to constrain the body of literature needed to gain an understanding of the investigated phenomena. The review of the specific body of literature corresponds to the second stage of the DRM methodology – Descriptive Study I. The selected literature sources need to be sufficient to describe the existing situation (the state of the art) and point out the aspects of design that are most suitable to address in order to improve the situation, but also to identify the knowledge relevant for evaluation of the potentially improved situation [30]. As such, the literature review step has focused primarily on the topics of the design process and activity decomposition, teamwork in design and experimental investigation of team designing. Moreover, as highlighted previously, the review included also the sources of knowledge in domains outside of engineering design (such as industrial, software and service design, product development and innovation management, cognitive psychology of design, etc.), thus satisfying the principle of utilising knowledge contained in different knowledge areas [70].
3) **Model development:** Within this research project, this prescriptive development step was conducted twice. First, the review-based support was developed by synthesising the literature review knowledge within a single theoretical framework. The support has been conceptualised in the form of a theoretical model of information processing and interactions in teams developing technical systems. This theory-based model has been intended primarily for framing the investigation of information-processing patterns observed in team design activities. Based on the guidelines for evaluation of experimental design studies and metrics, reported as part of the EDR [114], the theoretical foundation must be encompassed by identification, definition and measures of variables which are key to the observed phenomena. Unlike the review-based model, the second prescriptive development was based on the experimental data. Namely, a support in the form of a mathematical model has been developed by means of statistical modelling and by following the principles of developing scientific models from experimental design research [27]. The mathematical model prescribes relationships between different types of measured information-processing variables, whereas its implementation in the form of a computational tool enables simulation of differently set up team design activities. Hence, the ultimate purpose of the mathematical model is simulation of different

teamwork scenarios which are expected throughout the conceptual design stage and to gain insights relevant for both the understanding and management of design teamwork. Within the DRM, the steps of support development are assigned to the Prescriptive Study stage. It utilises the knowledge obtained from the available literature to conceptualise the intended support (model) and uses the understanding gained via additional experimental studies to deliver the final support (models, visualisations and simulation tools) [30]. These prescriptive steps have maximised the application of graphical representations (developed visualisations of team information processing and interactions) along with verbal explanations and mathematical-symbolic relationships, as a suitable language of design engineers [70].

4) **Experimental studies and model evaluation:** As it has been the case with model development, the evaluation of the models by means of experimental studies was conducted twice, first to test the review-based theoretical model (first experimental study) and later to test the mathematical model and the corresponding computational tool (second experimental study). In addition, these steps expanded the descriptive knowledge on designing in teams, and as such, coincided with the fourth stage of DRM – the Descriptive Study II. In the first experimental study, the theoretical model was employed for protocol analysis of team conceptual design activity. The protocol analysis study was built on the guidelines for human-focused research in engineering design [113], whereas the applied protocol coding scheme has been developed to reflect the elements and process granularity of the model's theoretical foundation. Besides expanding the knowledge on team conceptual design activity, the first experimental study provided data for the development of the mathematical model. The second experimental study utilised the mathematical model for computational simulation of specifically set up team conceptual design activities. The computationally generated experimental datasets were subject to new analyses, aimed particularly at developing new descriptive insights on designing in teams as well as validating the utility of the models. Validation here implies primarily the comparison with the insight reported in the available literature.

1.3. Scientific contribution

Valkenburg and Dorst stated that *"in order to improve team designing, we have to understand it, in order to understand we must be able to describe it"* [115]. The expected contribution of the research reported in this PhD thesis is concerned with the latter two – developing models for a valid description of team design activity and utilising the developed description to improve the general understanding of team design activity. These two aspects of scientific contribution are manifested through:

- Development of theoretical and mathematical models of information processing and interactions between individuals during team activities in the development of technical systems.
- Development of a teamwork activity simulation tool based on the proposed models, which can be used for better understanding, planning, management and support of team design activities.

1.4. Thesis structure

The thesis is divided into eight chapters which, to some extent, follow the previously described stages of the research methodology. The thesis structure is illustrated in Figure 1.1.

Chapter 1 introduces the research motivation and provides a brief overview of research aims and hypothesis, the adopted methodologies and the expected contribution driving the reported work. As such, the introductory chapter encompasses the outputs of the DRM's Research Clarification stage.

Chapter 2 summarises the literature review study and defines the research gaps. The literature review is reported in three sections, each aimed at presenting insights of a particular research area – the overall product development process as portrayed in the management research, the technical systems development stage of product development as prescribed in engineering design textbooks, and the team design activity as described by the recent efforts within the design research literature. The fourth section outlines the identified state-of-the-art research gaps and formulates research questions that guided the following work. The research background chapter corresponds to the Descriptive Study I stage.

Unlike the research associated to Research Clarification and Descriptive Study I stages, which is reported within Chapters 1 and 2 respectively, the research conducted as part of the Prescriptive Study and Descriptive Study II stages is spanned across multiple chapters (Chapters 3-8). As noted in Section 1.2, the model development steps and the subsequent experimental studies have been conducted as part of two iterative cycles.

Chapter 3 concerns the theoretical foundation of the thesis. There, the selected literature review insights are synthesised into a theoretical framework for the fine-grain decomposition and modelling of team conceptual design activity. Three fundamental design information processes are defined and associated with changing the state of the problem- and solution-related information entities. The resulting theoretical model and the associated visualisations are proposed as a means of investigating the proportions and sequences of design information operations during different types of team conceptual design activities. Regarding DRM, the theoretical framework chapter represents the outputs of the review-based prescriptive study (first iteration of the Prescriptive Study stage).

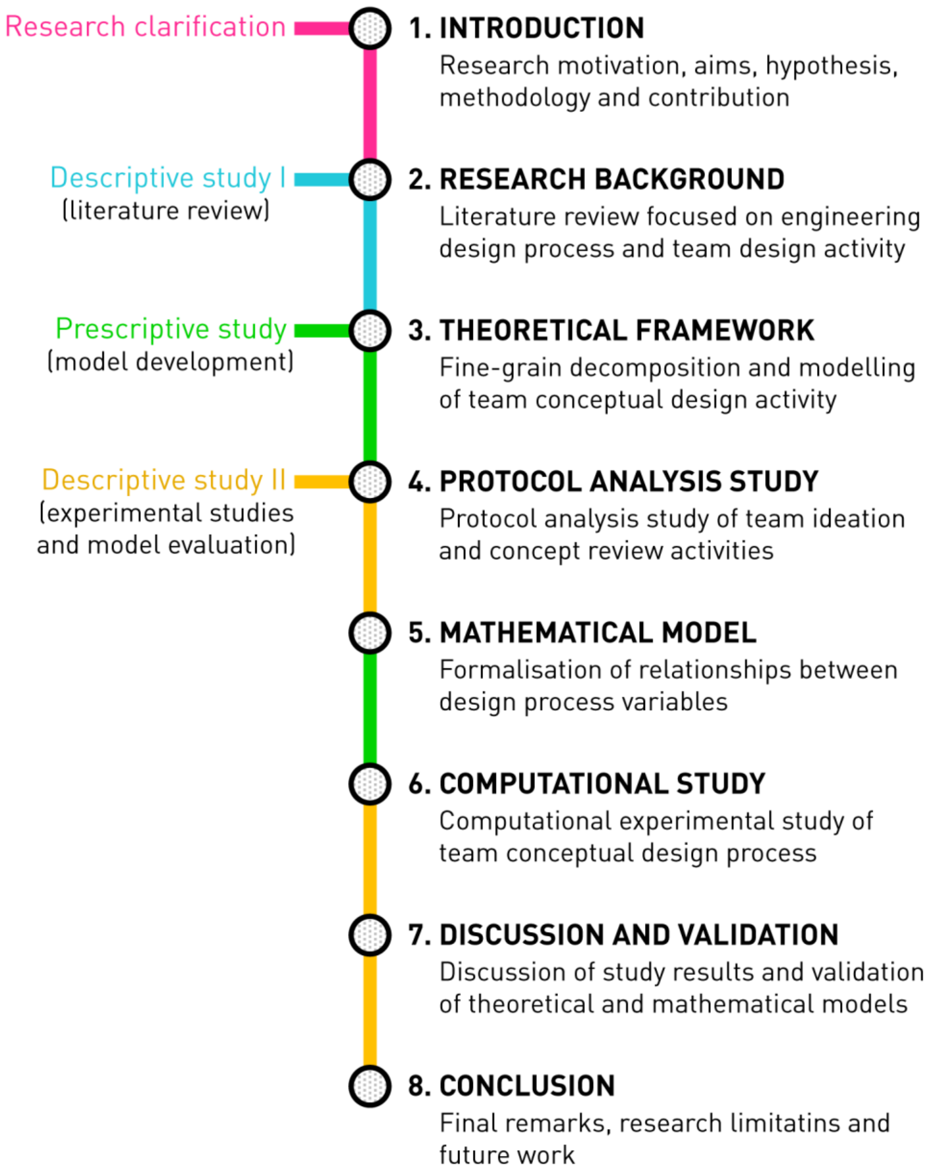

Figure 1.1 Structure of thesis chapters and corresponding stages of DRM

The developed theoretical model has been applied for the analysis of experimental sessions of two types of team conceptual design activity – ideation and concept review. The experimental investigation has been conducted in the form of a protocol analysis study and is reported in

Chapter 4. The results include descriptive and inferential statistical analysis of proportions and sequences of design information operations observed during the two types of conceptual design activities. By reporting on the information-processing patterns that are both common and distinctive for the two activities, the chapter corresponds to the initial implementation and evaluation of the review-based support, thus reporting on the work conducted within the first iteration of the Descriptive Study II stage.

Chapter 5 reports on the second iteration of the Prescriptive Study, where the data obtained in the protocol analysis study is used to develop a mathematical model. Regression modelling has been used to formalise the relationships in-between the variables that describe the proportions and sequences of design information operations. In addition, a computational tool has been developed with two main purposes: to facilitate the testing of the formalised regression models' predictive power, and to enable simulation of additional data concerning information processing and interaction patterns.

Following the development of the mathematical model and the associated simulation tool, Chapter 6 reports on the second (computational) experimental study. Namely, the mathematical model has been utilised as a means for a computational generation of data on information processing and interaction characteristic for the conceptual design stage of innovative and adaptive design projects. The simulated data has again been analysed in regard to information-processing patterns, thus expanding the descriptive outputs as part of the second iteration of Descriptive Study II.

The model and the data gathered via protocol analysis and computational studies are discussed and evaluated in Chapter 7. The chapter addresses the hypothesis and research questions raised in the first two chapters. Furthermore, the insights from the available literature have been used to discuss the protocol analysis and computational study results, along with the reflection on the theoretical and mathematical models and their potential application in research and management of engineering design projects.

In Chapter 8, the Descriptive Study II is concluded by reflecting on the expected scientific contributions, discussing the research limitations and providing guidelines for conducting future research regarding modelling of information processing and interactions in teams developing technical systems.

2. RESEARCH BACKGROUND

The second chapter summarises the Descriptive Study I. It reports on the most relevant literature concerning decomposition and categorisation of engineering design processes and team design activities in the context of product development. Particular attention is given to insights associated with team information processing in different stages and activities of technical systems development. Finally, gaps in the literature regarding the introduced research hypothesis are discussed at the end of the chapter.

The term "technical systems" represents all types of man-made artefacts, including technical products and processes, which are subject of the collection of activities performed by engineers as part of the engineering design process [116]. Just as technical systems fulfil user's needs by transforming objects from one state into another (desired) state, the engineering design work converts a need for a technical system into the detailed information from which the technical system can be produced [72]. Hence, engineering designers together with design methods and tools must ensure an appropriate flow of information that will result in a sufficient elaboration of the technical system.

The engineering design process, which is here referred to as transformation of engineering design information, is characterised by its layered and multifaceted nature. Namely, the workflow of an engineering design process consists of a number of specific tasks which can be further decomposed into flows of steps taken by the designers. On the other hand, engineering design represents only a fragment of an overall information transformation system – the product (technical system) development process. Any attempt to model the development process has embodied a selective viewpoint, and the state-of-the-art understanding can only be found by combining models and findings associated with different perspectives of the development [49]. Namely, given the hypothesis proposed in the introduction, the primary foci of here presented research are the modelling and analysis of team design activities. However, to be able to model team designing at various stages of the (conceptual) design and development of technical systems, and within projects of different levels of novelty (e.g. innovative and adaptive), the contextual overview of the overall product development process and engineering design has been made. Therefore, the literature review aims to introduce team design activity within a broader context of engineering design and product development.

The relevant literature review findings are presented in three parts, that is, based on three levels of detail the development of technical systems can be investigated on. The three levels correspond to the macro-, meso- and micro-level as defined by Wynn et al. [49]. At the macro level, the models focus on project structures and the context of the design process. Meso-level concerns the end-to-end flows of tasks, whereas micro-level models focus on fine-granular process steps, typically during individual or small group situations [49]. As shown in Figure 2.1, the three sections of literature review present the move from an overall macro-level perspective of product development (Section 2.1) to the meso-level investigation of the engineering design process (Section 2.2), and towards the micro-level descriptions of team design activity (Section 2.3). Centric to this approach is not only gathering of knowledge which can be synthesised within the model of team design activity, but also the identification of gaps in the literature and formulation of research questions that would guide the following research steps (Section 2.4).

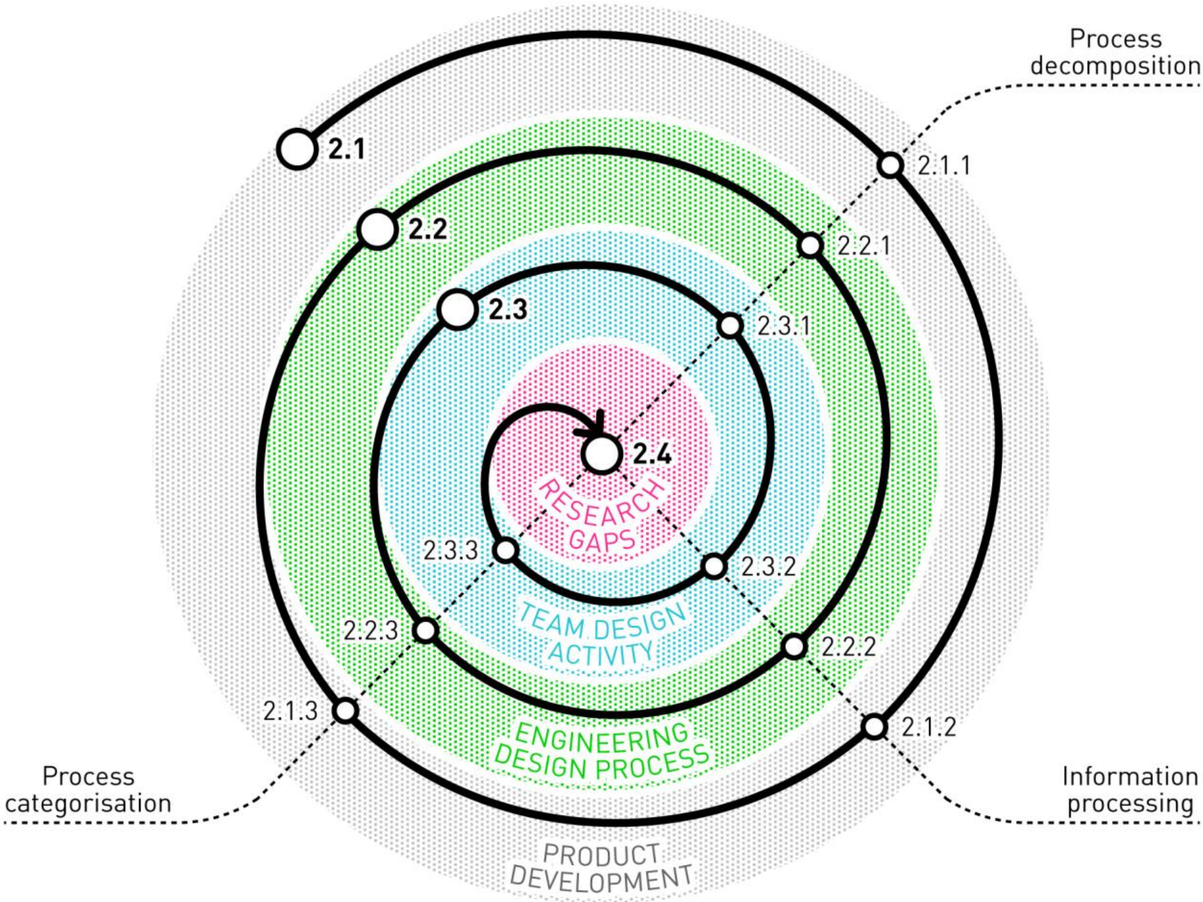

Figure 2.1 Overview of research background sections and their relation to product development, engineering design and team design activity processes, as well as decomposition, categorisation and information processing aspects of analysis

Moving towards the centre of the circle increases the granularity of analysis, but also represents a change from prescriptive (procedural) models of product development to descriptive (abstract and theoretical) models of design. Additionally, moving around the circle represents the addressing of different aspects of analysis. First, the decomposition of the process into smaller fragments facilitates the contextualisation of design information processing at different levels of design process granularity. The next aspect synthesises the research findings related to the nature and patterns of information processing characteristic for the decomposed fragments and the corresponding levels of process granularity. Finally, the process categorisation aspect enables identification of design information-processing patterns that relate to different types of technical systems being developed (e.g. types of projects), as well as different stages, tasks and activities within the development.

In doing so, the classification of information layers proposed by McMahon [117] is used when referring to stages, tasks, activities and operations within the design process. Stages are usually undertaken by inter-company teams and can last for months or even years and result in large-scale information packages. Stages represent workflows of tasks, such as functional or structural analysis, which are undertaken by work groups and can last from few days to several months. Furthermore, tasks can consist of several activities conducted by small teams and result in information objects such as sketches, CAD models, etc. Finally, individuals perform fine-grain operations and actions during design activities in order to develop entities, features and elements of information objects [117].

2.1. Product development: The big picture

The research on process-related practices in product development organisations is extensive and encompasses a wide range of studies that separate “the best from the rest” and prescribe appropriate ways of executing and managing product development activities. The resulting body of literature originates mainly from the management research (where the product development process is usually regarded as NPD); hence the focus is not solely on the engineering process but instead considers research, strategy and marketing activities along with the development of products. The research concerning NPD is here briefly presented to provide an understanding of the context in which engineering design takes part. Besides outlining the core product development stages and activities, the review is focused on identifying general types of information processing appearing throughout the stages as well as development variations discussed in the literature.

The reviewed prescriptive models represent the prominent and highly cited fragment of what is available in the product development literature. In order to place the design of technical systems (engineering design) in the context of the overall product development process, the review has been constrained mainly to the stage-based depictions of the NPD, since they explicitly distinguish engineering design (sometimes termed simply as technical development or just development), as a separate stage or workflow of activities. For a more comprehensive review of the special-purpose prescriptive models of the product development process, please consult recent literature studies on the topic of design and development processes (DDP) [49], [118], [119].

2.1.1. Decomposition of NPD process

The macro-level process in product development organisations is often represented using the stage-based models, which are easy to interpret and apply [120]. A stage is a subdivision of the product development process that relates to the state of the product under development. The low granularity of process representation is what makes stage-based models applicable in different environments and to different types of products being developed.

One of the commonly adopted models is the stage-gate system by Cooper [121], [122], which is both a process structuring approach and a representation of linear progress within stages of NPD. The main purpose of the stage-gate system is to give a prescriptive “idea-to-launch process” for new (innovative) products, following a set of best practice guidelines and including gate checkpoints to ensure quality. Depending on the company or organisational unit, stage-gate systems involve up to seven stages. Development, which includes the design of the product, is typically in the middle of the process, preceded by detailed investigation (building a business case) and followed by testing and validation [121]. Initially, Cooper and Kleinschmidt developed a general “skeleton” of the NPD process [5] in order to explore the best practice in executing NPD activities. Their study compared successful versus unsuccessful projects, and displayed the significant impact of frequent and proficient execution of designing-related activities on project outcomes, making them one of the key activities in the NPD process [5]. The authors additionally recommended to focus on the initial screening and market analyses in order to attain innovation success [5]. Over the decades, the original form of the stage-gate process has been altered in different directions, resulting in many different and tailored versions of the model, with built-in best practices that were not envisioned back in the early days [122]. The modifications have primarily been oriented towards loosening the process structure by improving the flexibility and scalability of the process based on organisations' specific needs. As a result, the original state-gate process may not be currently adopted by many organisations, however, the basic "idea-to-launch system" persists [122]. A recent adaptation of the stage-gate system by Schmidt et al. [8] compressed the typical stage-gate process into four stages: opportunity detection, preliminary marketing and technical assessment, development and testing (which includes design), and commercialisation. While the first stage-gate models represented NPD as a linear process, the newer model generations encourage concurrent (parallel) execution of the development activities [122]. Nevertheless, Hart and Baker argue that concurrency requires functional separation of tasks, whereas it is the results of these tasks that converge at decision points [123], [124].

The stage-gate has also been reinvented for use with paradigms such as "open innovation", "value stream analysis" and "agile development" and combined with the cost-cutting systems such as "Six-Sigma" and "Lean Manufacturing" [122], [125]. For example, the first implementations of agile (which was intended for the particular problems in software development), within stage-gate systems have shown the potential of increasing productivity and responsiveness to changing customer needs [126]. Agile-stage-gate hybrids look particularly promising in the case of high uncertainty and great need of experimentation associated with the development and testing stages of radical NPD projects [125]. Moreover, building every possible activity into each stage does not necessarily yield a good result, but rather a too bulky process. Lean and value-based approaches have thus been employed to dissect the process and maximise value-adding efforts and reduce non-value-added activities [122]. Finally, accommodation of open innovation into stage-gate systems has enabled flows of external ideas, technologies and intellectual property into the organisations, not only in the product screening stage but also in technical development [122].

In addition to NPD studies related to stage-gate models, there exists a significant amount of research on the process decomposition best practices in product development, carried out under the auspices of the Product Development and Management Association (PDMA). These reports are the continuation of the broad-based studies conducted by Booz Allen Hamilton (BAH) in 1968 and 1982 [127]. They described the development stage as an iterative translation of product ideas into product offerings [128]. Once the BAH studies were no longer accurate reflections of the state of the field, Page [6] conducted a new cross-sectional study sponsored by the PDMA, which reported on the status of NPD in the 1990s. Unlike the studies mentioned above, Page gave more attention to designing and highlighted the early design activities related to idea generation and concept development. According to Page, these activities are followed by the product development stage, which he characterised as pure technical work aimed at converting the concepts into working products [6]. In this way, the concept development stage, which includes creative activities such as brainstorming and preliminary team discussions about the product's design, has been separated from the development and testing stage, which are more technical. The supporting data confirms the presence and importance of the conceptual and product development activities in practice (more than 75% of respondents included these specific activities in their NPD processes). The following PDMA studies, conducted by Griffin [7] and Barczak et al. [9] have retained a similar frame of process activities while updating the trends and benchmarking the best practices. A somewhat detailed process decomposition can be found in a study by Song and Montoya-Weiss [129], who selected the most frequent NPD activities based on a combination of in-depth case studies and survey research. Activities which have been primarily related to design include: expanding ideas into conceptual solutions; evaluating development and manufacturing feasibility; determining product features (functions) and form; conducting engineering, technical and manufacturing assessments; prototype development; and final product design [129]. The most recent findings on NPD practices can be found in the PDMA Handbook of New Product Development [130] and within the continuously updated editions of Crawford and Di Benedetto's New Product Management [12], who provide a more extensive and granular decomposition of the NPD process from the management point of view. Simpler decompositions usually resulted in only two to three stages [131]. For example, Im et al. divide the process solely into the initiation and the implementation stage [132]. Lagrosen differentiate the idea, the development and the launch stages [133]. In a similar manner, Durmusoglu and Barczak separate the discovery, development and commercialisation [134], while Frishammar and Ylinepaa use the notions of early, mid and late stages [135].

The prescriptive approaches within the design research domain and from the engineering point of view have embraced the above mentioned stages in order to describe the interaction between the design process and the NPD context within which the design is delivered [49]. These approaches focus on integrating design activities with marketing and business aspects of NPD. For example, the Technological innovation methodology by Archer [136] decomposes NPD into an extensive list of tasks, making conceptual design activities part of the research stage, where market insights and technical feasibility of the concept solution evolve together. The Total Design by Pugh [137] provides a systematic methodology for the better integration of engineers and designers within the overall product development process, from market research to commercialisation. Similar aims can be found within the two notable engineering design textbooks: Integrated Product Development (IPD) by Andreasen and Hein [138] and Product Design and Development (PDD) by Ulrich and Eppinger [139]. Both represent the NPD process as a concurrent flow of marketing-, design- and production-related activities. In IPD, the designers are involved in determining the type of product, defining the working principles, preliminary and final design, as well as the potential adaptation based on sales and production. PDD puts additional emphasis on the strategic planning and technical/market screening activities, as well as the evaluation activities throughout the NPD process (e.g. concept evaluation and user testing studies).

In general, the macro-level approaches reported within the design research literature have coincided with the management point of view regarding NPD processes. Nevertheless, there have been attempts to revisit and expand the NPD practices from the design perspective. Fairlie-Clarke and Muller have thus developed a generic model of product development activities consisting of 18 generic elements [124]. Each of these generic elements comprises of a set of activities, which can be mapped onto the custom processes found in both the NPD literature and practice. Despite the sequential representation, authors emphasise that the NPD process does not imply rigid adherence to the sequence, nor any lack of integration or iteration of the generic activities [124]. Another distinctive depiction of NPD can be found in the form of a circularly structured model of the Delft product innovation process by Buijs [140], who made a comprehensive review of processes ranging from logical linear order to circular chaos. By not having the beginning nor the end, the circularly structured model suggests that introducing of new products results in reaction of competitors and new insights from the market, which are then reused as inputs for the following NPD projects. Moreover, such representation aligns with the argument that there is no clear beginning, middle and end to the NPD process, since, for example, one idea can prompt several products being developed [123].

A comparison of stages and activities described and prescribed within the aforementioned NPD literature is shown in Table 2.1. Throughout the years, the number of stages and nomenclature have been changing, but the basic prescription of the process persisted. The emphasis on decomposing the early stages as opposed to technical development and manufacturing is not surprising, considering that the focus of NPD literature is primarily on integrating the concept design activities with other front-end activities (e.g. market, customer and business analyses, and comprehensive screening before the product design is finalised).

Table 2.1 Comparison of NPD stages and activities as prescribed in selected literature

STAGE	ACTIVITY	Cooper [5], [121], [122]	BAH [127], [128]	Page [6]	Griffin [7]	Song and Montoya-Weiss [129]	Crawford and Di Benedetto [12]	Pugh [137]	Andreasen and Hein [138]	Ulrich and Eppinger [139]	Fairlie-Clarke and Muller [124]	Bujis [140]
Strategy development	Product line planning				●					●		○
	Product strategy development		●		●	●	●			●	●	●
Product screening	Product idea generation	○	●	○	○	●	●		○	●	●	●
	Market screening		●			●	○		○	●	●	
	Technical screening	●				●	○		○	●	●	
	Product idea evaluation		●	○	○	○	●			●	●	●
Business and market analysis	Market research	●	●			●	●	●	●	●	●	●
	Business analysis	●	●	●	●	●	●	●	●	●	●	
Technical development	Concept development	●	○	●	●	●	●	●	●	●	●	○
	Concept evaluation		○	●	●	○	●	●	○	●	●	○
	Detail design and engineering	●	●	●	●	●	●	●	●	●	●	●
Testing	Technical design testing	●	●			●		●		●	●	○
	Commercial design testing	●	●	●	●	●	●	●		○	●	○
	Trial production	●					●		●	●		○
Commercialisation	Production	●		●	●		●	●	●	●	○	●
	Market launch	●	●	●	●	●	●	●	●	●	●	●

● Activity discussed as part of NPD process
○ Activity acknowledged, but not explicitly included in process decomposition

In the last few decades, the macro-level studies related to NPD have also been revealing an increasing need for interdisciplinarity in NPD (e.g. [6]), either by temporarily integrating experts within the project team or via communication outside the project team boundaries. This need is particularly evident in the early stages of product development, including the concept development stage, where the technical and market aspects of product development must be integrated. Nevertheless, functionally distant tasks (such as the engineering design activities), often remain separated in the concurrent flow of activities [123], [124]; hence interdisciplinarity is not present at all times. The studies also reveal that different project stages are likely to relate to different nature of activity. For example, group ideation and decision-making are more likely in early stages, whereas the individual and technical engineering work are expected in the development stage.

2.1.2. NPD stage-level information processing

As argued in the introduction, the activities in the design process represent information-processing acts performed by members of a design team [76], [77]. Similarly, the overall NPD process (including the stakeholders involved) can be described as an information-processing system. Given the information-processing perspective, the NPD represents an interlinked sequence of information-processing activities which translate the knowledge of market needs and technological opportunities into information assets for production [141]. Namely, by processing the NPD-related information, stakeholders formulate product specifications, concepts, and design details, as long as all the information required to support production and sales has not been created and communicated [139].

The best practice studies have shown that successful NPD projects include ideation, screening and assessment activities in the front-end stage of product development (see Table 2.1). Hence, prior to formally starting a project, teams conduct idea generation [42], [128] and then select the most promising opportunity idea [5]. Preferably, this decision is made based on the information gathered through the market and technical screening activities [129]. Further steps combine investigation of the market and financial analyses to build a business case. Here, again, information about the user and market needs is collected, and economic analyses are performed, prior to the next step of feasibility assessment. At this point, the technical aspects of product information transition to the technical development stage, where the concept design is being detailed into an actual physical assembly or service. Once developed, the product can undergo testing – another particularly emphasised step in the NPD literature [6], [7], [9], [121], [122]. During testing, the product is being validated in-house and on field, and if necessary, trial sells and production activities are performed. The last stage is the production and commercialisation stage, where the designed product is being manufactured and launched onto the market.

According to the stage-gate representations of the NPD process, the stages reflect the state of the product being developed (in terms of information collected, generated, clarified, etc.), while the gates represent decision points, at which the project is assessed based on the available information. Studies suggest that acquiring, interpreting and sharing new information throughout the stages improves NPD decision-making at the gates [142]. Hence, there exist information requirements which define the purpose of stages in the process, whereas each stage is designed to gather particular information in order to reduce the uncertainties before decision-making [122], [131]. Consequently, the research efforts which utilise the information-processing view of NPD have mostly been focused on determining the information inputs and outputs for particular stages and decision points. For example, the ideal inputs of design-focused activities should include explicit assessments of user needs and technical requirements for concept development, and customer and production information for detail design [123]. The first should result in information about key attributes that need to be incorporated into the product and major technical cost, and the latter should finalise product specification [123].

In general, information processing within the stages of NPD related to the development of technical systems [143] involves recording, retrieving and reviewing of information [144], gathering, sharing and using of market information [145], acquisition, dissemination and implementation of information [146], [147]. In terms of design information, the NPD process has been considered an evolutionary process with design information being generated, transformed, and converged into the final product solution [148]. It can be argued that design teams implement the gathered (acquired and disseminated) market information, such as user needs and requirements to generate and transform a range of design information alternatives, before converging to a set of design information representing the final product design. However, studies with an overall perspective on the NPD process provide no clear insights about the dominant mode (or interaction of different modes) of design information processing during the particular NPD activities. These insights must be explored within the plentiful of theoretical and methodological research which describes and prescribes information processing during the specific types of development activities (some of which are presented later in this chapter).

2.1.3. NPD process categorisation

The proficiency and engagement in conducting general steps of the NPD process (e.g. activities reported in Table 2.1), is very likely to be affected by the type of the product being developed [129], and the corresponding uncertainty and risks inherited by the particular product category [12]. For this reason, the macro-level process categorisation is often closely linked to the type of the NPD project. While several criteria could be used for NPD project categorisation, the most useful relies on describing the degree of change a project presents to the organisation. Hence, the types of NPD projects are typically categorised in terms of the type of innovation they exhibit. Innovation, here referred to the creation of a product, service or process, can fall on a continuum ranging from “continuous” (evolutionary progress) to “discontinuous” (revolutionary progress) [149]. Researches have used different notions to categorise projects across this continuum. Garcia and Calantone provide an extensive overview of constructs and scales of technological innovation in the NPD literature [4] and show that the division of the continuum ranges from two up to eight levels of innovativeness. The most common, however, are the dichotomous and the triadic categorisation. On the discontinuous end of the dichotomous categorisation are the radical, really new, breakthrough, original and true innovations, while the continuous end includes the opposite notions of incremental, routine, reformulated and adoption. The triadic categorisations add constructs such as more innovative, platform, new generation and moderately innovative in the middle of the continuous-discontinuous spectrum.

A comparison of typical categories of NPD projects is shown in Table 2.2. Holahan et al. define radical, more innovative and incremental product innovation by utilising the standard project typology scheme [12], [150], which originates from the BAH studies [127]. They define **radical** product innovations as products that are new to the world and do not yet exist on the market (both technological and market uncertainty) [151]. The **more innovative** projects include product lines that are new to the firm (but not to the market), additions to existing product lines, and next-generation advances of products currently produced by the firm (either technological or market uncertainty) [151]. Finally, the **incremental** product innovations include improvements and revisions of existing products, repositionings (products that are retargeted for new users or applications) and cost reductions as the least innovative (neither technological nor market uncertainty) [12].

Table 2.2 Comparison of typical NPD project categories based on the type of innovation

<table>
<tr><th>Holahan et al. [151]</th><th>Clark and Wheelwright [152]</th><th>Booz Allen Hamilton [127]</th><th>Ulrich and Eppinger [139]</th></tr>
<tr><td rowspan="3">Radical product innovations</td><td rowspan="3">Break-through development</td><td rowspan="3">New-to-the-world products</td><td>Technology-push products</td></tr>
<tr><td>High-risk products</td></tr>
<tr><td rowspan="2">Generic (market-pull) products</td></tr>
<tr><td rowspan="3">More innovative product innovations</td><td rowspan="3">Platform or generational</td><td>New-to-the-firm products or new product lines</td></tr>
<tr><td rowspan="2">Additions to existing product lines</td><td>Platform products</td></tr>
<tr><td rowspan="2">Complex systems</td></tr>
<tr><td rowspan="4">Incremental product innovations</td><td rowspan="4">Derivative or incremental</td><td rowspan="2">Improvements and revisions to existing products</td></tr>
<tr><td rowspan="3">Customized products</td></tr>
<tr><td>Repositionings</td></tr>
<tr><td>Cost reductions</td></tr>
</table>

The notions of break-through, platform or generational, and derivate development introduced by Clark and Wheelwright [152] can be directly mapped onto the radical, more innovative and incremental categories respectively. However, they add a category of **research and development (R&D) and advanced development** to characterise projects focused on the creation of knowledge (technological explorations and investigations) as a precursor to commercial development [152]. Since these types of projects do not directly result in the development of technical systems, they have not been included in the comparison.

The associated risks and uncertainties of new product categories shown in Table 2.2 can best be described using the common variants of the product development process proposed by Ulrich and Eppinger [139]. These common variants can also, to some extent, be mapped onto the discontinuous-continuous innovation spectrum. For example, product development projects of highest uncertainty and risk (technical or market) concern the development of **technology-push** and **high-risk products**. The first utilises the “know-how” gathered through technological explorations and investigation to introduce new proprietary technologies to the market, and the latter entails unusually large uncertainties related to the technology or market; nonetheless, in the end, both are likely to introduce new-to-the-world products [139]. **Generic products** reflect the general stage-gate process, where product development starts with a market opportunity and then uses whatever available technologies are required to satisfy the market need [139]. Such a process can result in both new-to-the-world and new-to-the-firm products. Additions to existing product lines are usually based on **platforms**, where products are built around a pre-existing technological subsystem. At larger scales, platform products can be developed as **complex systems**, which comprise of many interacting subsystems and components. Different parts of complex systems can exhibit different levels of innovativeness; however, these are usually incremental improvements. Finally, **customised products** are the least innovative, as they represent slight variations of standard configurations and are typically developed in response to specific customer orders [139]. Ulrich and Eppinger introduce three additional variants of the generic product development process (process-intensive products, quick-build products and product-service systems) [139]; however, these processes do not involve the development of technical systems. In Andreasen and Hein’s IPD textbook, the characteristic types of new product development are more abstract and include **updating/replacing** existing products on existing markets as the incremental product innovation, **adaptation** of existing products for new areas of application or **supplementing** current areas of application with new products as more innovative product innovations, and **diversification** as the highest degree of innovation, in which new products are developed for new applications [138]. Aware that contemporary organisations often combine in-house and outside development, Andreasen and Hein provide different outsourcing strategies for organisations such as manufacturing firms, design companies, sales agencies, and other [138]. Various strategies are reflected in different starting points within the NPD process skeleton (e.g. across Table 2.1), whereas the sequences of the core development activities persist.

As emphasised by Garcia and Calantone [4], the reciprocal mapping of project typologies used across the literature is by no means straightforward, and the categories do not necessarily coincide as shown in Table 2.2. However, the separation of two extremes on the innovativeness continuum has provoked studies on the appropriate NPD practices for incremental, more innovative and radical product innovations. The studies generally agree that the development of really new products demands different approaches when compared to incremental product innovations. One of the first large scale studies (163 really new and 169 incremental products) was conducted by Song and Montoya-Weiss [129], who observed the perception of technical development as a most important stage for both types of innovation. Moreover, business and market opportunity analyses were perceived as more critical for radical innovation and strategic planning for incremental innovation. Such practice has been found counterproductive, as customer needs of really new products are often ill-defined and competitor capabilities are not clearly established. Thus detailed market studies provide no great value [129], particularly in the form of inputs for the subsequent technical development activities. Song and Montoya-Weiss explain that it is likely that customer requirements and technological capabilities co-evolve throughout NPD [129], which is aligned with the findings from the design literature presented later in the thesis. Their research prompted a number of new studies aimed at investigating the practices specific for incremental, more innovative and radical product innovations. The most relevant findings have been summarised in Table 2.3.

The succeeding studies have thus shown that radical projects are usually managed less flexible than incremental (e.g. in terms of skipping or overlapping gates) and include formal idea generation practices more often [151]. Also, radical product innovations are likely to exhibit more iteration [139] and require more information processing [153], [154]. Incremental projects often have abbreviated early front-end stages (or have none at all), whereas radical projects have messy, chaotic and fuzzy front-ends of the NPD process [155]. Moreover, the front-end activities of radical and incremental innovations differ extensively in the way in which problems are structured and in which information searches are initiated [156]. Differences have also been found in the project review practices. Incremental projects exhibit more efficient project reviews, which is reflected in a smaller number of review points and higher proficiency in using evaluation criteria when deciding on project continuation/termination [8]. Finally, the NPD process is more exploratory and less customer-driven for radical product innovations and often implies earlier development of prototypes [149].

Table 2.3 Selected findings regarding differences between incremental and radical projects

STUDIED PHENOMENA	INCREMENTAL PROJECTS	RADICAL PROJECTS
Relative rankings of critical development activities [129]	1. Technical development 2. Strategic planning 3. Commercialisation 4. Idea development and screening 5. Business and market opportunity analysis 6. Product testing	1. Technical development 2. Business and market opportunity analysis 3. Commercialisation 4. Idea development and screening 5. Strategic planning 6. Product testing
Process flexibility [151]	More flexible: – skipping gates: 60% – overlapping gates: 46%	Less flexible: – skipping gates: 38% – overlapping gates: 36%
Idea generation practices [151]	Informal / entrepreneurial	Formal
Iteration [139]	Less	More
Information processing (via communication) [153], [154]	Less (routine incremental)	More (nonroutine radical)
Early front-end activities [155]	Abbreviated or none at all	Messy, chaotic, fuzzy
Problem structure initiation [156]	– Identified and/or structured by organisation – Directed to individuals for information search	– Identified and/or structured by individuals – Individuals direct and conduct information search
Project review practices [8]	– Less review points – Higher proficiency of evaluation criteria usage	– More review points – Lower proficiency of evaluation criteria usage
Nature of development [149]	– Less exploratory – More customer-driven – Later prototyping	– More exploratory – Less customer-driven – Earlier prototyping

From the design perspective, the insights regarding nature of development and project constraints tend to be similar. Andreasen and Hein claim that it is not the type of activities or their sequence within the process that create the difference between very innovative and less innovative projects, but the extent to which things are predetermined – the so-called “degree of freedom” a design has [138].

Insights summarised in Table 2.3 will be used to define the parameters of the computational experimental studies of adaptive and innovative design projects (Chapter 6). To better explore the design and development stages of technical systems development, the following sections shift focus to textbook knowledge and research in engineering design (and design in general). This body of literature provides higher granularity depictions of the technical development stages, as well as dominant modes of information processing appearing throughout the process.

2.2. Engineering design process

In the engineering design literature, technical development is often portrayed as a series of stages, each of which further concretises the design by creating more concrete information about it [49]. Textbook knowledge in the engineering design domain is based primarily on the industrial practice observed by the early researchers. Unlike the NPD literature which encourages an approach of incorporating a comprehensive set of product development activities (especially marketing activities), engineering design research gives more attention to the designing as the core of technical development. Engineering design textbooks supply engineers with systematic approaches, methods and tools for dealing with common engineering design tasks. Due to their establishment in engineering design education, the prescribed methods and procedures are likely to be followed in real-world development organisations. At the same time, descriptive design research and empirical studies of design provide feedback on how design is really performed.

2.2.1. Decomposition of engineering design process

Several relevant textbooks on engineering design (and product development in general) have been reviewed in order to discern the main stages in the development of technical systems. Here presented review aggregates the common design steps prescribed in these textbooks. The in-detail review included the following:

– Pahl and Beitz: *'Engineering Design – A Systematic Approach'* [41]. One of the most widely referenced models of engineering design, both in industry and education (several textbook editions) and a foundation of VDI 2221 guideline [144] for systematic development and design of technical systems and products.
– Hubka and Eder: *'Engineering Design'* [112]. A comprehensive procedural model of technical systems development. The model builds on the concept of a transformation system, which has been introduced throughout Hubka and Eder's previous work [116], [157]. In short, each transformation consists of a transformation system which transforms operands from one state into another by utilising effects given by the operators (e.g. humans, tools, environment, etc.). In the case of technical systems development, the

design process is transforming needs, requirements and constraints of a technical system into a detailed description of a technical system (e.g. instructions for what would need to be manufactured) using the effects of engineering designers and their working means, methods, management and environment. The same approach was utilised in *‘Introduction to Design Engineering’* by Eder and Hosnedl [158].

- Ullman: *‘The Mechanical Design Process’* [159]. Another well-accepted textbook gives an overview of the product development process with a particular focus on mechanical design and the accompanying tools and methods. Ullman expands the traditional engineering design process with product discovery and planning stages and associates them with organisational rather than with project activities.
- Cross: *‘Engineering Design Methods: Strategies for Product Design’* [160]. Based on the review of prescriptive and descriptive design literature, Cross introduces a model of designing that integrates the procedural aspects of design with the structural aspects of design problems. Cross emphasises that the stages and accompanying design methods should not be assumed to constitute an invariant design process.
- Eggert: *‘Engineering Design’* [161]. The textbook makes a distinction between engineering analysis and engineering design. The solution to an analysis problem is a predicted behaviour, and the solution to a design problem is a form. Performing engineering analysis means formulating an analysis problem, solving it and validating the results. Performing engineering design on the other side means formulating a design problem, and then iterating between generating and analysing alternatives, and, in the end, evaluating the feasible ones.
- The review also included *‘Product design and development’* by Ulrich and Eppinger [139] and *‘Integrated Product Development’* by Andreasen and Hein [138], which have been preliminarily discussed within the previous section. Both books represent the processes and methods from three main perspectives: marketing, design and production, thus proving the need for integrating these disciplines during development projects.
- Several additional textbooks have initially been screened, including *‘The Engineering Design Process’* by Ertas and Jones [162], *‘Engineering Design’* by Dieter and Schmidt [163], *‘Engineering Design Process’* by Haik and Shahin, and *‘Engineering Design: A Project Based Introduction’* by Dym et al. [164]. However, the provided decompositions of the engineering design processes to a large extent coincide with what is reported within the aforementioned literature; hence a more extensive review of these books was omitted.

There exist many commonalities across the textbooks, particularly in high-level process descriptions. Firstly, the scope of tasks is similar, particularly regarding task clarification, conceptual design, embodiment, and detail design stages. Some authors include project planning activities as part of the design process (e.g. [41], [138], [139], [158], [159]), while others assume product idea as an already developed input to the design process. On the other hand, some of the models expand the late-design, by separating stages such as production ramp-up [138], [139], product support [159], and organisation and documentation of design outputs [164]. Nevertheless, a common process of technical systems development has been outlined hereafter, based on the aggregated steps. The process consists of five stages which are further decomposed into core engineering design tasks, as shown in Table 2.4. The stages have been described as follows:

1) **Planning** is usually performed before the approval of the product development project. For this reason, only several textbooks consider planning task as part of the engineering design process. Planning stage typically starts with the analysis of the situation in the market and organisational context. Once the organisation develops an understanding of competitors' products and own competence, it can start searching and evaluating product opportunities (product ideas). Various sources of opportunities exist, both within and outside the organisation. Product ideas which have been evaluated as feasible and align with the organisation's strategy become product development projects. A product definition together with resource allocation and schedules are formulated as project inputs.
2) **Task clarification** is performed to determine clear project aims and collect and define requirements and constraints to be fulfilled by the technical system. Designers first gain an understanding of the problem and, depending on the type of a project, perform detailed investigation of the state-of-the-art concerning similar products on the market and customers' needs. Designer's involvement in identifying customer needs is encouraged, and a number of methods for these tasks are provided in the abovementioned textbooks. Once a sufficient amount of information needed for problem definition has been collected, design teams develop product specification – an accurate and measurable description of what the product has to do in the form of requirements and constraints. It is not unusual for product specification and requirement list to be updated on several occasions throughout the development process.
3) **Conceptual design** is on average given the most attention in the textbooks and is described as a stage that transforms requirements into concepts – typically implying functional models of the product being developed. It generally starts by abstracting the

design problem and establishing a function structure as a refinement of the functional requirements. By decomposing the main product function into sub-functions, the team can focus on what the product must do, rather than how it will do it. Designers then address each sub-function and transform them into a larger number of distinctive working principles which, to a varying extent, fulfil the sub-functions. The combination of working principles on the level of the function structure forms the basis for concept alternatives. Such a systematic approach is suggested to facilitate the generation of diverse concepts. In order to select the most suitable concept solution, teams evaluate concept alternatives and make a decision which alternatives (one or multiple) will be further developed. The team then refines the alternatives and documents the decision.

4) **Embodiment design** can encompass several highly iterative design steps, depending on the type of technical system being developed. First, the product architecture is resolved by defining the overall layout of the technical system, primarily by arranging the components and defining modules for more complex designs. Then, as part of configuration design, the team defines components' forms, materials and manufacturing processes, and conducts engineering analyses (e.g. calculation and simulation). Designers often utilise Design for X (DfX) principles to address the issues of manufacturability, assembly, reliability, ergonomics, costs, maintenance, environment, safety, etc. These steps result in a preliminary design, which again must be evaluated. Finally, once the decisions about the main form, materials and manufacturing have been made, the design can be optimised (e.g. parametric analysis) and tested. It is important to notice that prototype testing might appear at several points earlier in the process. However, most textbooks highlight its importance within the embodiment design stage. Moreover, as the team approaches the final design and the associated production processes, a more detailed cost analysis can be performed. Preliminary part lists and production documentation are prepared as stage outputs.

5) **Detail design** concerns the finalisation of documentation related to the design of the technical system, such as the final product specification, detail drawings of parts and assemblies (with tolerances and surface properties) and bill of materials. The final documentation also includes instructions regarding production, assembly, transport and operation. Although many formal meetings have been made up to this point in the process, a final design review is desirable towards the end of the engineering design project. The final design review is the most structured and comprehensive one and results in management's decision on whether the product design is ready for production.

Table 2.4 Overview of engineering design tasks prescribed in the reviewed textbooks

STAGE	TASK	Pahl and Beitz [41]	Hubka and Eder [112]	Ullman [159]	Cross [160]	Eggert [161]	Ullrich and Eppinger [139]	Haik and Shahin [165]	Dieter and Schmidt [163]	Dym, Little and Orwin [164]
Planning	Situation analysis	●					○		○	
	Opportunity identification	★		●			★		○	
	Opportunity evaluation	★	○	●			●		○	
	Economic analysis		○			○	●		●	
	Product definition	●		●		●	●		○	○
	Resource allocation and scheduling	●	○	●		●	●			
Task clarification	Problem clarification	●	●			○				●
	State-of-the-art (competition) research		●	●		●		●	●	
	Customer needs identification	○		●	○	●	●	●	●	○
	Product specification	★	●	●	★	★	●	★	★	★
Conceptual design	Function structure development	●	●	●	●	●	●	●	●	●
	Working principles search	★	●	★	★	★	★	★	●	★
	Concept generation	●	●	●	●	★	★	○	★	★
	Concept evaluation	★	●	●	★	★	●	●	★	★
	Concept selection and refinement	★	●	★			★		★	○
	Document concept decision			●		●				
Embodiment design	Architecture design	●	●	●		●	●		●	
	Configuration design (form, materials, calc.)	●	●	●		●	○	●	●	●
	Design for X	●	○	●		●	●	●	●	●
	Preliminary design evaluation	★	●	○		●			○	○
	Optimisation	●	●	○		●	○	●	●	●
	Prototyping and testing	○	○	○		●	●	●	●	●
	Cost analysis	●	○	●				●	●	○
	Preliminary documentation preparation	●	●					●		○
Detail design	Detail drawings elaboration	●	●	●		●	●		●	●
	Procedures and instructions documentation	●	●	●		○				●
	Final design review	○	○			○			●	

● Task discussed as part of the engineering design process
○ Task is optional, not described in detail or included in different stage of engineering design process
★ Team activity is encouraged in solving the task

The comparison of design tasks included within the reviewed systematic approaches to engineering design (Table 2.4) reveals that the procedural models coincide predominately within the conceptual design stage. Moreover, some of the textbooks aim primarily on providing a methodology for the development of conceptual solutions (see, e.g. [50], [160]). Hence, both design researchers and educators are aware that conceptual design makes the highest demands on designers and offers the most scope for improvements if the creative potential is properly harnessed [104]. During embodiment, it is common that needs for further conceptual developments arise (usually minor refinements) in respect of particular functions.

The decomposition represented in Table 2.4 furthermore reveals that, for several design tasks, the textbooks encourage performing of team activities rather than individual work. Team activity is particularly favoured when the tasks require idea generation, or solution finding, evaluation and refining [41], [139], [159], [163], [164]. Thus, according to the majority of textbooks, team activity is most desirable during tasks such as defining product specification, searching for working principles, concept generation and evaluation, selection and refinement of concept solutions, and design reviews. Such recommendations suggest that one should search primarily within the conceptual design stage when investigating team design activity. Indeed, design research has shown that design teams tend to organise team sessions mainly during tasks related to concept proposal [61], [107]. These insights have facilitated the identification of team activities which have been experimentally investigated in Chapter 4, as well as the formulation of the conceptual design process simulated in computational experiments in Chapter 6.

Finally, it is important to notice that although most of the design work is performed individually, engineering design textbooks emphasise that information sharing and good teamwork are essential at all times. The following subsection explores the decomposed engineering design process in terms of prescribed information-processing practices.

2.2.2. Information processing in engineering design

According to Lawson and Dorst [53], the systematic approach to design corresponds to the "design as problem-solving" paradigm. If designers are studied, regardless of whether individuals or teams [159], one can observe that they perform something similar to posing a problem, searching for solution alternatives, exploring and evaluating the consequences, and selecting the most suitable alternative – the so-called generate-evaluate-select pattern [53]. While this paradigm does not capture aspects such as creativity or learning, it can describe how designers process information.

Models of engineering design thus acknowledge the problem-solving approach to designing. For example, Hubka and Eder define basic design operations – stating the problem, searching for solutions, evaluation and deciding, providing and preparing information, verifying, and representing – which are most frequently used by design engineers and are present during all activities [112]. Pahl and Beitz describe each stage as a journey through a problem-solving cycle, from problem confrontation and information collecting, followed by definition of objectives and main constraints, towards creation and evaluation of solution information. In the end, based on all information available, a decision is made about the final solution [41]. Similar descriptions of the problem-solving cycles are present in most of the reviewed sources, with some optional steps, such as the communication of decision instructed by Ullman [159].

Problem solving requires a large and continuous flow of information. Pahl and Beitz recognise three main categories of information conversion to describe problem-solving from the information-processing perspective: reception, processing and transmission of information [41]. Information is received from different types of sources (formal and informal information gathering) and can again be transmitted by documenting (sketching, drawing, reporting, etc.) or verbally communicating information. On the other hand, information is processed by performing analysis and synthesis, concept development, calculation, experimentation, layout elaboration, solution evaluation [41]. Maarten Bonnema and Van Houten utilise Krumhauer's [166] perspective and argue that information processing modifies the conceptual design space in three dimensions: complexity, concreteness and realisation. "Abstraction" information process decreases concreteness and "search for solution" increases both concreteness and realisation of design, while "division into subproblems" decreases and "combination and selection" increases complexity [32]. Such a description of design problem solving aligns with the arguments made in the introduction: when solving design-related problems, human designers can be regarded as information processing systems [167].

The IPS perspective is not present in prescriptive design research only. A lot of what is known about design cognition and human designers' problem solving stems from empirical research that utilises the IPS conceptualisation [168]. The resulting design theories aim at describing practices that are regularly taken as design, while prescriptive design theories aim to single out particular types of design practices and posit desirable properties about these practices [169]. For this reason, the problem-solving sequence of understanding, generating, evaluating and decision-making [159] can be discerned on different levels of the engineering design process [138]. On the project level, an overall, ill-defined complex problem is solved. On the stage level, the problem-solving steps can be recognised in the sequences of tasks (e.g. tasks within the conceptual design stage as shown in Table 2.4). Finally, at the lowest level, teams tackle simpler, more defined problems, preferably using different types of design methods.

In general, researchers agree that the design process is not linear whereby design problems could initially be fully defined and then solutions directly derived from them [66]. Empirical research has shown that in the case of ill-defined problems, designers do not typically start by pursuing to define the design problem rigorously [97]. They instead progressively and iteratively discover, structure and address the issues as they emerge in the design process [170]. The nonlinearity of the design process and the ill-defined nature of design problems is particularly evident during the conceptual design stage, which assumes reciprocating decomposition of design problems and exploration of possible solutions before a final concept is proposed [171]. A comparison of descriptive and prescriptive insights into the main information processes associated with conceptual designing is shown in Table 2.5. Even when designers follow a systematic problem-solving strategy (e.g. [172]), they continuously generate new task goals and redefine task constraints [173]. Two distinctive dimensions of design space – the problem space and the solution space – are developed through a constant iteration of analysis, synthesis and evaluation (ASE) processes [174], [175]. These three fundamental information processes can be traced back to Asimow [176], who proposed ASE model as a general problem-solving strategy, and Watts [177], who presented the design process as iterative cycling through ASE. The evolution of problem- and solution-related information entities, which is a result of ASE information processes, is often regarded as “problem-solution co-evolution”.

Table 2.5 Comparison of information processes associated to the conceptual design stage

<table>
<tr><th>TASK</th><th>Pahl and Beitz [41]
Hubka and Eder [112]</th><th>Fiorineschi et al. [172]</th><th>Maarten Bonnema and Van Houten [32]</th><th>Cross and Dorst [174]
Woodehouse and Ion [75]</th></tr>
<tr><td rowspan="2">Function structure development</td><td rowspan="2">Problem defining</td><td rowspan="2">Analysis</td><td>Abstraction</td><td rowspan="7">Cycles of analysis, synthesis and evaluation</td></tr>
<tr><td>Division into subproblems</td></tr>
<tr><td>Working principles search</td><td rowspan="2">Solution creation</td><td>Information gathering</td><td>Search for solutions</td></tr>
<tr><td>Concept generation</td><td>Synthesis</td><td>Combining</td></tr>
<tr><td>Concept evaluation</td><td>Solution evaluation</td><td rowspan="2">Evaluation</td><td rowspan="2">Selection</td></tr>
<tr><td>Concept selection and refinement</td><td>Decision</td></tr>
<tr><td>Document concept decision</td><td>Communicating</td><td></td><td></td></tr>
</table>

The notion of problem-solution co-evolution has been introduced within the co-evolutionary model of designing by Maher et al. [178] and has been present in many studies ever since, especially within the design creativity research. In the model, designers iteratively develop concepts and explore the problem and solution spaces, with each space informing the other. Maher and Tang later investigated the utility of co-evolution as a cognitive and a computational model of design and demonstrated the similarity of reasoning between the human designer's cognition and computational algorithms co-evolutionary cycles [83]. However, studies have also shown that despite the commonalities in information processing employed by human designers, their focus on problem or solution space can differ and that the co-evolution strategies can be distinguished as problem- and solution-driven [179].

Although there exists an overlap in how systematic approaches to engineering design prescribe the conceptual design stage (see Table 2.4 and [180]), Table 2.5 and the empirical research on the high-level information processing reveal that the conceptual design process is not straightforward and there is no linear or sequential representation of the information flows that could capture conceptual design information processing. Later sections will show that as the granularity of design process descriptions increases, the more flexibility and iteration is required in the models to capture the information processing.

2.2.3. Engineering design process categorisation

Similarly to the product development processes, the categorisation of engineering design processes is commonly associated with outputs of engineering design projects, that is, how distant the design outputs are from the current paradigm, primarily in terms of novelty [42]. The most referenced and simple categorisation comes from Pahl and Beitz [41], who proposed three types of design:

- **Original design** incorporates new solution principles which can be realised either by selecting and combining known principles and technology or by inventing completely new technology. The design of the original technical system is novel, without existing or predecessor systems [158]. Sometimes (but rarely) it is the identified need that is original [163]. The term is also used when existing or slightly changed tasks are solved using new solution principles [41].
- **Adaptive design** implies keeping known and established solution principles to satisfy a different need. The design team adapts the known solution (embodiment) to the changed

requirements [163]. It may, however, be necessary to undertake original designs on the level of individual components or assemblies [41].

– **Variant design** involves varying the size or arrangements of components and assemblies within the limits of previously designed products [41]. The systems' function and solution principles remain the same, whereas some of the design parameters are changed [163]. As such, variant design implies a direct adoption of a previous technical system [158].

Howard et al. have compiled plentiful of analogous categorisations which can be found in design research [42]. Notions used to describe original design have thus included "new", "innovative", "novel", "radical" and "creative". Adaptive design has been described as "extensional", "strategic", "redesign" and "innovative", whereas variant design has been characterised as "transitional", "modular/architectural" and "configuration". One could suppose there exists a relation between these three categories of design with the previously discussed types of NPD projects, that is, original design with radical projects, adaptive design with more innovative projects and variant design with incremental projects (e.g. [181], [182]). While these two categorisations share many similarities, unification regarding originality and novelty is yet to be established [183]. For example, McMahon suggested that both adaptive and variant design can be classified as incremental [184].

Comparison of the three types of designs/design projects has been the subject of several studies. Selected findings are summarised in Table 2.6. Studies build upon the fact that for a variant design the function structure [41] and solution elements/patterns [185] of an existing product can be reused as a starting point for engineering development. Hence, the creative outputs, if any, are most likely to appear within the embodiment design stage [186], as a result of a structural level change in the technical system [42].

In adaptive design, the function structure is established by analysing the existing product and adapting the functions with respect to the new requirements [41]. The creative outputs are thus most likely to be functional [42] and appear during task clarification [186]. Therefore, as opposed to variant design, adaptive design can only partially reuse solution elements and patterns available within the adapted technical system [185].

On the other hand, the original design demands that the function structure is generated from scratch, based on the requirements list and abstraction of the given design problem [41]. The process can produce creative behavioural outputs [42], as a result of conceptual design efforts [186]. No or little a priori solution elements and patterns are available for original design [185].

It can thus be argued that the difference between the two ends of the novelty spectrum determines how far the formulation of the design problem needs to be abstracted away from the salient features of the design elements and patterns that perform similar functions in technical systems [187]. This difference is reflected explicitly in the levels of uncertainty associated with the three types of design. For example, during the conceptual design stage, original projects exhibit the highest amount of uncertainty since no baseline product can be determined, whereas adaptive and variant designs present less uncertainty due to solution reuse. Nevertheless, as the development proceeds, the uncertainty continually decreases for all design types [44], [188].

Table 2.6 Selected findings on differences between variant, adaptive and original design

PHENOMENA	DESIGN PROJECT TYPE		
	Variant	Adaptive	Original
Amount of conceptual design uncertainty [44], [188]	Small	Medium	Large
Function structure development [41]	Based on existing function structure	Based on analysis of existing products	Based on requirements list and abstract problem formulation
Use of existing solution elements and patterns [185]	Complete reuse of priori given solution elements/patterns	Partial reuse of priori given solution elements/patterns	No or little priori given solution elements/patterns
Creative outputs [42]	Structural level	Functional level	Behavioural level
Relative position of creative outputs [42], [186]	Embodiment design	Task clarification	Conceptual design
Dominant type of reasoning [189]	Deductive design processes	Inductive design processes	Abductive design processes
Space expansion [190]	Restrictive partitioning		Expansive partitioning

Additionally, the variant, adaptive and original designs can be associated with deductive reasoning (inferring an individual instance from a general principle or law), inductive reasoning (generalise a set of instances or observations) and abductive reasoning (creating a possible hypothesis that explains a set of observations) processes respectively [189]. Summers [191] explains that in the engineering design context, deductive reasoning takes place when the design variables and knowledge are given, and the design specifications are derived; inductive reasoning seeks to generate appropriate design knowledge based upon the given set of design variables and specifications; whereas abductive reasoning may be viewed as a mapping to possible design variables based upon the given design specifications. A similar view is provided by Lu and Liu [192], who represent deductive reasoning as a logic foundation of design analysis, inductive reasoning as a logic foundation of design evaluation and abductive reasoning as a logic foundation of design synthesis. Abductive reasoning creates new hypotheses, deduction analyses these hypotheses before induction justifies them [192]. Hence, within the variant design, the design team dominantly validates the appropriateness of an existing design and makes minimal adjustments on its design specification. In the adaptive design, the team analyses the current design and reuses some of the functions and solution principles, whereas, in the original design, the team must hypothesise the complete design.

Studies related to the development of the innovative design-focused C-K (Concept-Knowledge) theory (see, e.g. [193], [194]) make a clear distinction between rule-based design and innovative design. In the context of rule-based design, the focus is on preserving the system (such as the same or similar customer requirements, stable market, reuse of technical skills and knowledge, anticipated risks, etc.), whereas the exploration activities are not the objective [190]. Within such logic, innovation is possible but is limited to a continuous improvement of existing products and technologies (incremental innovation) [190]. In contrast, innovative design provokes a renewal of the system through investigation of new specifications, competences, knowledge, markets, risks, etc. (radical innovation) [190]. Innovative design requires avoiding of universal and fixed object identities by means of expanding partitioning of concept sets, where the properties added to the design concepts consist of entities that the designer or the design team are not knowledgeable of [194]. On the other hand, restrictive partitioning implies adding entities of properties known to the designers.

There is no consensus on the proportions of original, adaptive and variant design in product development. In their study conducted in the UK industry, Culley et al. report 36% of original, 36% of adaptive and 28% of variant design projects [195]. According to Pahl and Beitz's study of mechanical design projects in Germany, 25% of them were original, 55% adaptive and 20% variant [195], [196]. Another UK-based study [197] revealed that original design was undertaken by 33% of the companies, adaptive by 92% and variant by 33%. All three studies are over 20 years old, and the data can be considered outdated. A more recent study [198] suggests that 83% of companies undertake adaptive, 57% original and 14% variant design.

In the context of here presented research, the focus is set on original and adaptive design only (see Chapter 6 for more details). Besides variant design being the least present in engineering design practice according to studies above, there are two interdependent reasons for such a constraint. First, since variant design assumes complete reuse of existing functional structure and solution principles and can only produce creative design in the embodiment design stage and at a structural level (see Table 2.6), the conceptual design stage can be partially or fully skipped. Second, it was mentioned that team activities are most likely to take part during the conceptual design stage (see Table 2.4). Hence, the insights that here presented research aims to provide can only be related to adaptive and original design projects, where a complete execution of the conceptual design stage is expected.

2.3. Team design activity

In the introductory chapter, it is highlighted that researchers adopt numerous perspectives of the engineering design process to study the team design activity. While there exist differences in the way researchers explore and model design, its multifaceted nature is well recognised [46], [53]. For instance, in their domain-independent descriptive model of design, Reymen et al. [199] introduce the notion of a design situation, which combines three facets of design: the state of the product being designed, the state of the design process, and the state of the design context. According to their model, designing is the activity of transforming the state of the product being designed or the design process into another state towards the design goal. They also utilise the notion of design space to refer to possible states of information about the product and the process. The state of the design context, on the other side, is separated from designing and is changed by the stakeholders (e.g. user requirements, company norms, available production technologies, etc.). Moreover, while designing is affected by the context it takes place in, context-related information itself most often does not change within the time span of design activities [199], such as ideation or design review sessions. Hence, according to the design situation viewpoint, team design activities represent sequences of designers' information-processing actions towards a design goal, which result in the evolution of information entities within the explored design space (transforming the state of the product and the process) considering the specific (static) design context.

Before the theoretical framework of team design activity can be comprehensively elaborated, several areas of relevant research on both individual designers and design teams are examined. As a starting point, the experimental studies of team designing are considered, as a means of decomposing the process into design operations and gaining a better understanding of what drives information processing in design teams. Next, the role of ASE design operations and design space information evolution across different models of the design process is investigated. Finally, insights into different types of team design activities are briefly discussed. However, it is important to notice that the examined areas are not mutually exclusive. For example, the experimental studies often utilise observable design actions and the change in design space as a proxy for investigating the thinking processes of designers.

2.3.1. Decomposition of team design activity

Given the viewpoint of thinking and cognition as the underlying processes of designing, particular attention in micro-level design process research has been given to decomposing and modelling of designers' thinking/cognitive processes. For many years now, design researchers have been employing approaches such as think-aloud and conversational methods, case studies and controlled experiments to explore thinking patterns during the execution of design tasks [23]. Design thinking research is inspired by other disciplines that currently study collective thought, including social and cognitive psychology, organisational sciences and anthropology [200]. Fine-grain investigations of the designing have thus often been carried out using protocol analysis, currently the most suitable method of revealing the cognitive actions of designers [174]. Reported protocol studies of design teams are mainly concurrent and conversational [101], meaning that the participants concurrently report on their thinking acts using conversation during task execution. The resulting cognitive models usually describe the iterative nature of designing in which design alternatives are repeatedly generated, analysed and evaluated through exploration and convergence [170], [201].

A noteworthy example is the "generic model of design team activity" by Stempfle and Badke-Schaub [54], who employed protocol analysis to capture regularities in thinking and reasoning processes underlying the problem-solving process of three laboratory teams. Their study proposes a model that reflects the "natural" thinking process of design teams, where the generation of solution ideas is followed by immediate evaluation, except when there are any questions or misunderstandings. If such quick assessment yields a positive result, teams decide to accept the solution. Otherwise, new solution ideas are sought [54]. Ensici et al. [202] provided additional detail to the decision process by focusing on the phenomena of using and rejecting decisions, based on whether the selected solution elements have been included in the final solution proposal. They decomposed the team design process into thinking processes related to decision making and identified the consequences of rejected decisions, such as narrowing the solution space and prioritisation, structuring and complexity reduction of the design problem [202]. Sauder and Jin [56] decomposed design activity into generative thinking processes of memory retrieval (when an experience or design entity that existed in the past is remembered), association (when connections are drawn between two design entities), and transformation (when a design entity is altered or changed). They link these cognitive processes to the observable design operations which designers perform as a response, and the stimulation that appears due to design operations [56]. They observed that the stimulation occurring through questioning has the strongest relationship with the generative thinking processes. Cardoso et al. [203] investigated thinking in design teams during ideation and decomposed it as an inquiry-driven process. They observed patterns of cognitive moves triggered by reflection on dissatisfaction and facilitated by the formulation of high-level questions that steer the direction of the design discourse. Sung and Kelley [204] analysed sequences of cognitive strategies of design teams and identified a bi-directional iteration between designing and predicting, or simply put – introducing ideas and predicting possible consequences of the ideas. In addition to the thinking processes, Eris et al. [58] discussed the significant role of gestures in team designing. For example, they identified that gestures which construct conceptual relations between two sketches (cross-gestures) facilitate the shared understanding of designers.

Although the above-listed studies provide valuable insights into team design thinking, the used protocol coding schemes are closely tied to the specific context and the phenomena observed, making it difficult to directly compare the results and conclude how team design activity is affected by the change in design context or progress of the design process.

In contrast to the use of diverse coding schemes, there exists a portion of experimental design studies that investigate various aspects of design team thinking processes using a single coding scheme – the function-behaviour-structure (FBS) ontology of design and designing. These studies have accepted the axiom that *"the foundations of designing are independent of the designer, their situation and what is being designed"* [26]. The FBS ontology describes all designed things (artefacts) irrespective of design discipline whereas its three fundamental constructs are defined as follows: function describes 'what the artefact is for', behaviour represents the measurable attributes that can be derived from artefact's structure, and structure represents artefact's components and their relationships [26]. Kan et al. [205] utilised the FBS ontology-based coding scheme to study an industry team brainstorming session and measure frequencies of transitions between FBS design issues and interactions on the individual and team level. Jiang et al. [55] applied the same ontological framework to study design cognition of small teams within the context of different disciplines and conceptual design tasks. They classified the teams' designing styles as problem- and solution-focused. As an extension of that research, Gero and Jiang [206] studied the design review and critique sessions. Both studies reveal commonalities across designing but also identify the differences between design domains and design tasks. Gero et al. [207] investigated how different creativity techniques reflect in design cognition of team members during the concept generation activity. They coded the activity of eleven design teams and found a correlation between the structuredness of ideation techniques and design teams' focus on the problem or solution-related aspects of designing.

In the case of employing the unified FBS coding scheme, different types of activities and design processes as well as different team compositions can be investigated and compared, particularly the cognitive processes regarding the design space (functions, behaviours and structures). However, FBS being an ontology that primarily describes the design as an artefact, the elements of the design process are derived from transitions (transformations) between the coded segments as part of the extended FBS framework, rather than being directly coded. Additionally, since only transitions between certain pairs of FBS design issues are assigned with micro-scale processes, the FBS transformative processes-based coding scheme may not be suitable for direct coding of the observable design process.

Within the context of the presented research, the abovementioned experimental studies of team design thinking are relevant for two main reasons. Firstly, they provide valuable methodological insights into the development of a protocol analysis study (Chapter 4). Secondly, the studies have contributed an extensive collection of insights into different aspects of team information behaviour, which can be utilised for comparison, interpretation, validation and discussion of the research results (Chapter 7).

2.3.2. Information processing in team design activity

All design processes are different unless examined at a very abstract level [208]. Studies aimed at unfolding the commonalities and differences amongst designing in different domains confirm this by indicating that only at the high level of abstraction can information behaviour similarities between different domains be recognised (e.g. [199], [209]). Any comparison of different individuals, teams, activities, domains or methods, whether in search for similarities, patterns or differences, stems from the prerequisite of abstraction in modelling both the design process (e.g. design information processing) and the design space (e.g. design information entities). Therefore, the fine-grain descriptions of individual or team design activities have predominantly been given in the form of abstract micro-scale models, which emphasise the iterative nature of designing and the need of responding to new information generated or revealed during the design process [49].

A well-adopted example of process abstraction implies design information operations of analysis, synthesis and evaluation (ASE), which have already been discussed as a means for meso-level modelling of engineering design information processing. Information processes analogous to ASE can thus be identified across eminent descriptive models of design activity. For example, the "basic design cycle" by Roozenburg and Eekels [210] consists of analysis, synthesis, simulation, evaluation and decision. The "design steps" by Gero [211], which represent the previously introduced transitions within the FBS framework, include analysis, synthesis, evaluation, formulation and reformulations. These transitions are also present within the extensions made to the FBS framework. For example, in the extension by Cascini et al. [212], analysis, synthesis and choice are used to describe routines such as identification of needs and formulation of requirements. ASE has also been included in the "iterative processes" between the problem and the solution space in creative design by Dorst and Cross [174]. Their portrayal of ASE as fundamental design information processes in designing has been embraced across many studies in design research (see, e.g. [67], [213], [214], [215], [216], [217]). The "generic step model of team design activities" by Stempfle and Badke-Schaub [54] consists of "generation", "analysis", "evaluation" and "decision". The "integrated model of designing" (IMoD) by Srinivasan and Chakrabarti [218] classifies generic activities into "generate", "evaluate" (which can also include analysis), "modify" and "select". Although the aforementioned abstraction using ASE can be related to models of problem-solving in design [219] and creative process models [42], [220], the ASE sequence which has been intended as a model of sequential stages in the design process was often criticised for not reflecting the reality of design projects [173]. Namely, the iterative nature of designing prevents the straightforward analysis-synthesis-evaluation execution of the design process.

To avoid ambiguity, from this point on, the term **design operation** is adopted when referring to ASE as the observable fine-grain acts of design information processing that transform the state of design information entities (as opposed to the stages in the design process). Moreover, the design information entities manipulated by means of design operations will be referred to solely as **design entities**. Such conceptualisation is inspired by the study of Jin and Benami [36], who introduced the notion of design operations when referring to the observable, fine-grain acts of design information processing. In their generate-stimulate-produce (GSP) model, design operations are used to generate design information entities, which in return stimulate designer's thinking processes, leading to new design operations. The model gives a clear distinction between the observable aspects of the designing such as talking, writing and sketching, and the internal ones such as the underlying thinking processes of designers [36]. GSP was initially utilised to investigate creative patterns and stimulation of individual designers but was later expanded into collaborative thought stimulation (CTS), where design information entities are shared by team members [56]. However, since the CTS model regards design operations only as generators of design information entities (design information synthesis), the notion of design operation must be adjusted to reflect also the previously discussed analytic and evaluative design information processes (design information analysis and evaluation), which are performed in both the problem and the solution space.

The insufficiently understood role of ASE design operations in the co-evolution of the problem and solution space is in part a result of inconsistency in the interpretation of ASE as fine-grain steps in the design process. Firstly, depending on their purpose, the models of design tend to associate analysis to either the problem or the solution space. The prescriptive design models inherit the problem-solving interpretation of ASE, where analysis is information processing performed within the problem space and includes the understanding, decomposition and formulation of design requirements (e.g. [75], [172]). Although such instantiation of analysis can also be found in some of the descriptive approaches (e.g. [210], [221]), the others of the aforementioned descriptive models associate analysis to information processing within the solution space, performed to increase the understanding of solutions prior to evaluation. These models introduce concepts such as formulation [211], goal clarification [54] and problem definition [222] to summarise problem space information processing. Secondly, although synthesis has been shown to play an equally important role in developing both design problems and solutions [223], its integration as part of the ASE sequence within prescriptive and descriptive models is primarily in the form of generating solution-related information [224]. Thirdly, with new information entities populating the problem space as designing proceeds, the co-evolutionary process implies not only the need for evaluation of information about design solutions but also evaluation of the introduced requirements and constraints [83], [101]. However, the term evaluation has mainly been used to describe the assessment of design solutions concerning the problem being solved, e.g. in the FBS framework [55], problem-solving steps of design teams [54] or the creative processes in design [42], [220]. Problem evaluation remains a phenomenon that has not been explicitly included within the reviewed ASE design models.

The explored design space (problem and solution) evolves as new design information entities are generated, and the existing ones are modified. Different types of design information entities appearing in the problem and the solution space have been abstracted in more-less similar ways.

For example, the reasoning about requirements, functions and expected behaviour of the artefacts within the FBS ontology is related to the problem space, and reasoning about structure and structure's behaviour is related to the solution space [55]. Macmillan et al. [25] have used the terminology of needs, requirements and problems as conceptual design entities in problem space, and solutions, proposals and concepts as entities in solution space. In their study of the solution- and problem-driven design, Kruger and Cross [179] categorised the problem entities into requirements and constraints. Sarkar and Chakrabarti [225] recognised requirements, related problems, constraints, solutions and evaluation criteria. Liikkanen and Perttula [171] used the terms goals and subgoals in the exploration of problem decomposition. On the other hand, the IMoD by Srinivasan and Chakrabarti [218] classifies entities of the problem-solution space solely into generic requirements and solutions, thus eliminating the issue of vague boundaries between some of the terms describing entities in the design space. For example, functions and behaviour (see, e.g. [175], [226]), needs, requirements and constraints (e.g. [212], [227]), or how ideas become concept solutions (e.g. [107], [228], [229]). Based on these findings, here presented research will not consider detail classification of design entities but will instead use the concepts of problem and solution space to cover the full range of design entity expressions (as shown in Chapter 3). Therefore, the design entities (either problem- or solution-related) represent sets of properties, whereas each new combination or addition of properties results in a new design entity added to the design space. Such conceptualisation of design entities coincides with that of propositions within the concept and knowledge spaces of the C-K theory [193], [194], in that adding or subtracting properties from existing design entities does not result in their modification, but rather in the creation of new entities.

The generality and applicability of co-evolutionary design are yet to be comprehensively tested for team conceptual design. In their domain-independent descriptive model of design, Reymen et al. [199] have implemented the problem-solution co-evolution as a simultaneous evolution of current and desired properties. Hultén et al. [20] have related their model of ideation to problem-solution co-evolution by introducing the concepts of common ground and transformative closure. The first implies returning to the problem space with a new understanding of the problem, and the latter implies reaching a solution space that can develop and change during the process. They emphasise the need for conceptualising the common understanding (ground) as support for co-evolution within the models of designing in teams [20]. Recent studies support the co-evolution during collaborative activities such as ideation [46] and concept selection [230], but also throughout a series of real-world product design meetings [67]. Moreover, a study by Deken et al. [63] has shown an increased alternation between the spaces during conceptual design compared to the task clarification stage.

As part of their C-K theory, Hatchuel and Weil [194] claim that ambiguity, ill-defined issues and poor project wording are not problems or weaknesses, but a necessary part of design. More precisely, C-K theory treats vague and ill-structured problems (as defined by Simon) as “a semantically-clear and well-formulated departure point” [231]. Hence, in a way, it does not recognise design problems or design constraints as deterministic (or problem space as such). Rather than focusing entities of problem and solution spaces, C-K investigates the concept space and the knowledge space [193], as well as the mutual interplay between them, thus capturing both the generation of solutions and generation of knowledge about concept behaviour via analysis [185]. Nevertheless, the co-evolution of concept and knowledge spaces implies that the design work will meet an undefined number of “problems”, where constraints will be investigated and selected [231]. These descriptions are, to a great extent, in line with the above-reviewed studies.

Finally, it must be noted that there also exists another stream of team design activity research that focuses on information processing associated with aligning the design process (planning of further steps, moderating, etc.). Nevertheless, a study aimed at understanding human information processing during team design tasks revealed that over two-thirds of strategies employed by the designers were searches through design space, as opposed to coordinating the design process [54], [77]. Moreover, focusing on the management of designing rather than the designing itself is more related to the research of team roles [57], coaching and leadership [37], experience and expertise [79], team adaptation [232], etc. For these reasons, here presented research concerns solely the information processing acts (design operations) related to creation and modification of design content information (design entities). The extension of these concepts within a theoretical framework is described in Chapter 3.

2.3.3. Common team design activities: Ideation and concept review

The literature review revealed that there exists no clear categorisation of team design activities within the design research. Nevertheless, two distinctive categories of team design activities have often been investigated: ideation-based activities (e.g. idea and concept generation) and review-based activities (e.g. concept/design review, concept evaluation). In particular, ideation and concept review are considered core activities within the overall design process, due to their creative potential and impact on the final design outcomes respectively [46], [230]. Significant research efforts have thus been directed towards prescribing approaches, methods and tools to facilitate the generation of high-quality ideas and selection of best concept solutions in a particular context. The prescriptive research has primarily been aimed at boosting creativity and productivity, but also overcoming fixation and bias (please consult [233], [234], [235], [236], [237] for more details on recent findings concerning these issues). Although there are many formalised methods developed for ideation and concept review, it is often suggested that designers prefer using informal and ad-hoc methods rather than the less intuitive and imposed formal and structured methods [236], [238], [239]. For example, a study with experienced students has argued that when provided with TRIZ (structured method) and morphological analysis (partially-structured method), designers tend to follow a process that resembles unstructured brainstorming towards the end of the design session [207]. Nevertheless, studies aimed at comparing the design process in different disciplines suggest that the designers' behaviour tends to be both domain- and experience-dependent. In addition to the positive correlation between the structuredness of concept generation methods and reasoning about design problems [207], studies have shown that industrial designers (teams) tend to be more problem-focused when compared to mechanical engineering designers [55], [206]. Moreover, studies investigating differences between novices and experts reveal higher proportions of problem-focused issues in the process of novice designers, whereas the more experienced designers tend to use solution conjectures [97], [171], [179], and may as such be less subject to structured design methods.

Understanding the designers' natural (intuitive) and informal approaches to designing (both the cognitive and the observable process) is essential in providing teams with better support during activities such as ideation and concept review. Despite the acknowledged need for understanding the naturally occurring information processing in design, fine-grain decomposition of ideation and concept review processes has rarely been in focus of design research. Moreover, the comparison of the two activities is, again, hindered by the use of different coding schemes, team formations, design environments, etc. Nevertheless, some additional process and behaviour patterns identified across the protocol studies of ideation and concept review are discussed below.

Sarkar and Chakrabarti [225] studied idea generation of individual designers and identified different patterns of design space search taking place during problem understanding, solution generation, and solution evaluation, and related the types of searches to solution quality. They later propose a model of ideation where, given an unsolved problem, designers find a related existing solution from the past (from memory), and then they modify it for the current problem, whether in the phase of problem formulation, solution generation or solution evaluation [240]. Liikkanen and Perttula [241] also perceive ideation as a memory-based activity which consists of memory sampling and idea production. They have pointed out that individual designers generate similar initial ideas before contextual cueing and verbal stimulation are introduced. However, a semantically substantial and associatively rich change of context and verbal stimulation are shown to alter the ideation process.

Stimulation has also been the subject of team ideation studies. López-Mesa et al. [242] studied the effect of stimuli coupled with individuals' problem-solving styles on the ideation of design teams. They argue that stimulus with images leads to a higher quantity of solutions, while stimulus by idea-prompting checklist favours refinement of solutions. Sauder and Jin [56] employed retrospective protocol analysis and found that collaborative prompting and clarification have a strong relationship with remembering design entities, while collaborative seeding and correcting strongly correlate to altering and changing design entities.

Cash and Štorga [46] have explored what drives generation of creative ideas by using network analysis to link ideation to the engineering context and the broader design process. Insight derived from the networks include identification of decoupled ideation, characterised by producing numerous solution ideas, and integrated/iterative ideation, expressed in co-evolution of design problems and solutions. Hatcher et al. [243] have embodied Linkography to compare the creative processes when two different ideation methods are used (brainstorming and an approach proposed by the authors). Their findings include, for example, that brainstorming has a less structured approach and is more likely to contain a higher number of idea moves (idea generation) inspired by non-idea moves, such as questions (idea analysis).

Protocol studies of concept review (and the more general design review) activity have primarily been in focus of design research with educational implications (see, e.g. [244]), such as guidelines for mentors who provide feedback, advice or critique. However, little is known about the team-based concept review process and how teams select creative ideas [61]. Moreover, while concept review is generally described as a convergent activity [236], Toh and Miller [230] note that team members often not only evaluate and select concepts, but also combine, modify, and propose new solution ideas. They point out that teams who pursue to generate new ideas during concept review tend to select more creative concepts.

The FBS framework has also been used to investigate different types of design activities. As mentioned earlier, it has been employed to study design cognition during both ideation (e.g.

[55], [205], [207]) and concept review [206]. Since the FBS ontology offers commensurability of study results [26], these studies can be qualitatively and quantitatively compared. Gero and Jiang [206] identified the similarity between ideation and concept review manifested in the linearity of cumulative occurrences of structure and behaviour issues. However, they noticed that unlike designing (ideation), concept review activity does not exhibit the decrease in the ratio of the problem- and the solution-related discussion as the session progresses. Aside from these efforts, the micro-scale descriptions of how teams synthesise, analyse and evaluate design entities during concept review remain undeveloped.

Within the context of the presented research, the studies of ideation and concept/design review offer insight into key characteristics of these activities, thus complementing the general findings resulting from experimental research on team design thinking when discussing the protocol analysis results in Section 7.3.

2.4. Research gaps

The overview of research on team design activity in the context of engineering design and product development has facilitated the identification and formulation of the main research gaps. The gaps particularly concern the agreement on definitions of analysis, synthesis and evaluation as fundamental operations in design problem solving and their application in exploration of problem space and solution space; as well as lack of understanding on how the team problem-solving process is adapted as teams progress in conceptualisation of the technical system. The gaps are briefly discussed hereafter and summarised in the form of research questions which are addressed later throughout the thesis.

Given the perspective of the simultaneous evolution of design problems and solutions [174], and ASE being regarded as different modes of conceptual thinking [75], the context of presented research calls for adopting the appropriate definitions of ASE as design operations performed within and in-between the problem and solution space, as well as for developing means of measuring and representing of how these design operations are performed within the time frame of team design activities. Rather than attributing information processing either to the problem or solution space, the formulated definitions of ASE should highlight the differences between analysis, synthesis and evaluation as fundamental information-processing mechanisms for evolving the design content. Moreover, the measurements and representations should facilitate identification, capturing and characterisation of various design operation patterns that might appear during team design activities.

RQ1 What definitions, measures and representations of analysis, synthesis and evaluation can be utilised to capture and model the fundamental information-processing mechanisms that design teams perform to manipulate the problem- and solution-related design information content?

Moreover, as shown throughout the thesis, both the notion of problem and solution space and ASE as fundamental information-processing mechanisms have regularly been employed in investigation and modelling of design activity. Nevertheless, while the proposal of co-evolution of design problems and solutions [178] has been around for over twenty years, the questions of how exactly ASE sequences iterate and intertwine throughout the conceptual design stage, and in what way these patterns differ for the problem and the solution space, have not been extensively explored. For example, the fine-grain approaches used to understand the details of micro-scale cycles [49] in conceptual design activities have either employed ASE sequences within the solution space (e.g. [54], [207]), neglected the evolution of both spaces (e.g. [172]), or focused solely on individual designers (e.g. [221], [225]). Insights into patterns of ASE and the evolution of the explored design space should complement the existing models of team design activity and increase the understanding of team conceptual design process.

RQ2 What patterns of ASE altering inside and in-between the problem space and the solution space can be identified during team conceptual design activities?

Additionally, experimental studies have generally been tied to only a specific type of conceptual design activity, such as ideation (e.g. [203], [207]) or concept review and selection (e.g. [61], [230], [237]). The utilisation of diversified team compositions, coding schemes and modelling approaches in these studies hinders direct comparison of the results. Because of the inability of a proper inter-study comparison and due to the lack of studies offering a simultaneous investigation of team designing across different activities, there exists little understanding of how the micro-scale design process patterns are affected by the design activity goal and team's progress within the conceptual design stage.

RQ3 In what way do the identified patterns of ASE design operations differ for different types of team conceptual design activities, particularly for ideation and concept review?

RQ4 In what way are the identified patterns of ASE design operations likely to be adjusted with the progress of the conceptual design stage?

Finally, the reviewed literature shows that while teamwork is expected during the entire NPD process, the team design activities, where a group of designers explicitly work together on a design task, are encouraged mainly within the conceptual design stage. As such, team activities within the conceptual design stage have been given significant attention, and there exist efforts to model different aspects of team designing, including information processing and interactions in teams. Nevertheless, the overall context stemming from NPD and the engineering design process within it remains neglected. In particular, there exist no insights on how information processing and interactions in teams are affected by the novelty or type of innovation characterising the technical system being designed, despite it being the primary way of categorising projects in both NPD and engineering design literature.

RQ5 What are the prevalent patterns of ASE design operations in different types of engineering design projects, particularly regarding the novelty of the developed technical system (innovative and adaptive design)?

The research questions have been tackled as part of model development and experimental studies steps described in Section 1.2. In the first cycle of prescriptive and descriptive development, the relevant literature findings have been synthesised into a theoretical model of team conceptual design activity. The resulting theoretical framework directly responds to the research question RQ1 (Chapter 3). The descriptive step of the cycle involved a protocol analysis study of team conceptual design activity aimed at gaining insights needed for addressing research questions RQ2 and RQ3 (Chapter 4). The second prescriptive-descriptive study cycle involved mathematical model development and computational experiments needed for generating data relevant for research questions RQ4 and RQ5 (Chapters 5 and 6). Insights reported across Chapters 3–6 are summarised and discussed in Chapter 7, by addressing each of the research questions separately.

3. THEORETICAL FRAMEWORK

In this chapter, the most relevant insights from the reviewed literature have been synthesised into a single theoretical framework. Three main parts can be discerned. First, the definitions of analysis, synthesis and evaluation as design operations within both the problem and the solution space are formulated. Second, the design operations and spaces are incorporated into a state-transition model of team conceptual design activity. Finally, the theoretical framework is encompassed by identification, definition and measures of variables which are necessary for the fine-grain analysis of team conceptual design activity.

Analysis, synthesis and evaluation have thus far in the thesis been conceptualised as information-processing mechanisms performed by designers to manipulate the design information content in the problem and the solution space. Any further theoretical developments first require adoption and adaptation of concise definitions of ASE, which would fit them within the previously formulated notions of design operations, design entities and transitions between states of the design content and process (as described in Subsection 2.3.2). In addition, the definitions of ASE must embrace and reflect various notions of information processing discussed in Subsections 2.1.2 and 2.2.2. As shown in Section 3.1, the micro-level process terms such as “generate”, “clarify”, “simulate”, “formulate”, “decide”, “select”, etc., can all be reduced to ASE – the fundamental building blocks of the design process, irrespective of the design domain, the type of design problem being solved or the current progress in stages of technical systems development. The resulting increase in level of abstraction has been expected to improve recognition and comparability of information-processing patterns emerging during team conceptual design activities. Once formulated, the definitions of design operations and their interaction have been embedded within a single model of team conceptual design activity (Section 3.2) to enable identification and description (Section 3.3) of patterns of analysing, synthesising and evaluating problem- and solution-related design entities.

3.1. Fine-grain decomposition of team design activity

Considering the diversity in interpretation of ASE within the reviewed micro-scale models of the design process, the first step in framing the team conceptual design activity implies developing clear definitions of analysis, synthesis and evaluation. The definitions must reflect the conceptualisation of ASE design operations as fundamental mechanisms for evolving/co-evolving the design entities within both problem and solution space. First, the notion of team conceptual design activity has been considered within the domain-independent descriptive model of design by Reymen et al. [199]. In the model, the evolution of the design space (problem and solution) is represented by a set of states, where the act of designing transforms one state into another. If designing is decomposed into design operations, then ASE design operations express the transitions between the states of the design space. Figure 3.1 illustrates the sequences of design operations as transitions driving the evolution of the explored design space (change of the state of the product being designed and the state of the design process) while approaching the goal of the design activity.

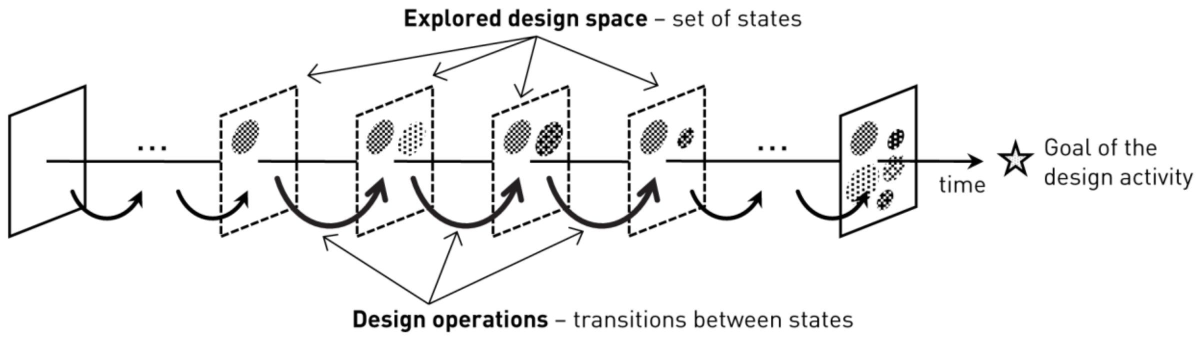

Figure 3.1 Design operations as transitions between states of explored design space (adopted from [199])

In the presented research, the ASE design operations have been defined by adapting the categorisation system for verbal activities in design teams by Casakin and Badke-Schaub [222], since, unlike most of the models, it presumes similar mechanisms for exploration of both the problem space and the solution space. Hereafter, the ASE design operations as transitions between the states of the explored design space have been defined as follows:

– **Analysis** is a state transition resulting in an increased understanding of a particular design entity within the explored design space. When performed in problem space, the purpose of analysis is to clarify different aspects of the design problem (needs, requirements, constraints, etc.). Analysis in problem space corresponds to “explanation” as defined by Casakin and Badke-Schaub [222]. The goal of conducting analysis in solution space is to increase the understanding of the proposed solutions to the problem (ideas, concepts, alternatives, etc.). Analysis in solution space can be performed by determining or learning the behaviour of a solution (how the proposed solution works/behaves) or by clarifying the structure (building shared understanding) of a solution entity.

- **Synthesis** is a state transition resulting in the appearance of a new design entity within the explored design space. Solution synthesis includes also the improving, refining and combining of solution entities, since the original design entities (the ones being improved/refined/combined) remain in the solution space, and new derivatives appear. As such, solution synthesis corresponds to "new solution idea" as defined by Casakin and Badke-Schaub [222], that is introducing a solution entity that addresses a particular problem/subproblem, or developing new aspects of a previously introduced solution entity. Problem synthesis corresponds to what Casakin and Badke-Schaub [222] call "problem definition" and includes operations aimed at defining and structuring elements of a given design problem.
- **Evaluation** is a state transition resulting in the assessed appropriacy of a particular design entity within the explored design space and in the context of a given design problem. Evaluation of a design entity (in problem or solution space) is performed by addressing a criterion, that is the relevant design entity in the problem space (requirement, constraint, etc.). Two different scenarios of performing evaluation have been identified based on the problem decomposition techniques described by Liikkanen and Perttula [171]. In the first one, the problem space design entities (criteria) are explicitly identified before the execution of evaluation design operation. In the second scenario, the problem entities (criteria) are introduced implicitly within the team at the moment of performing evaluation design operation. Although the goal in both cases is assessing the appropriacy of a particular design entity (problem or solution), in the second scenario, a new problem entity (criterion) emerges in parallel to the evaluation design operation. For example, McDonnell [245] describes the scenario of detecting "misfits" during solution evaluation, which can lead to reframing the problem. In a similar matter, Harvey and Kou [246] explain that the role of evaluation during creative group tasks is not only to provide feedback and make decisions but also to frame the problem. Solution evaluation corresponds to the assessment of a solution idea by focusing on its value and feasibility, as defined by Casakin and Badke-Schaub [222]. They, however, do not propose any verbal activities concerning problem evaluation. Nevertheless, the proposed framework assumes that design entities appearing in the problem space can likewise be evaluated. Hence, problem evaluation is considered as a means of assessing the appropriacy of the new requirements, constraints or subgoals.

The fundamental difference between synthesis and analysis is that as a result of the synthesis design operation a new design entity appears in the explored design space. The fundamental distinction of evaluation design operations is that it also envelops the criterion by which the manipulated design entity is assessed. Figure 3.2 illustrates how ASE design operations act as transitions between the states of the explored design space. The illustration has been simplified by merging the problem space and the solution space into a one-dimensional design space. It must be noted that Figure 3.2. illustrates only a single scenario of performing a sequence of ASE design operations and that it does not imply that such sequence is dominant in design.

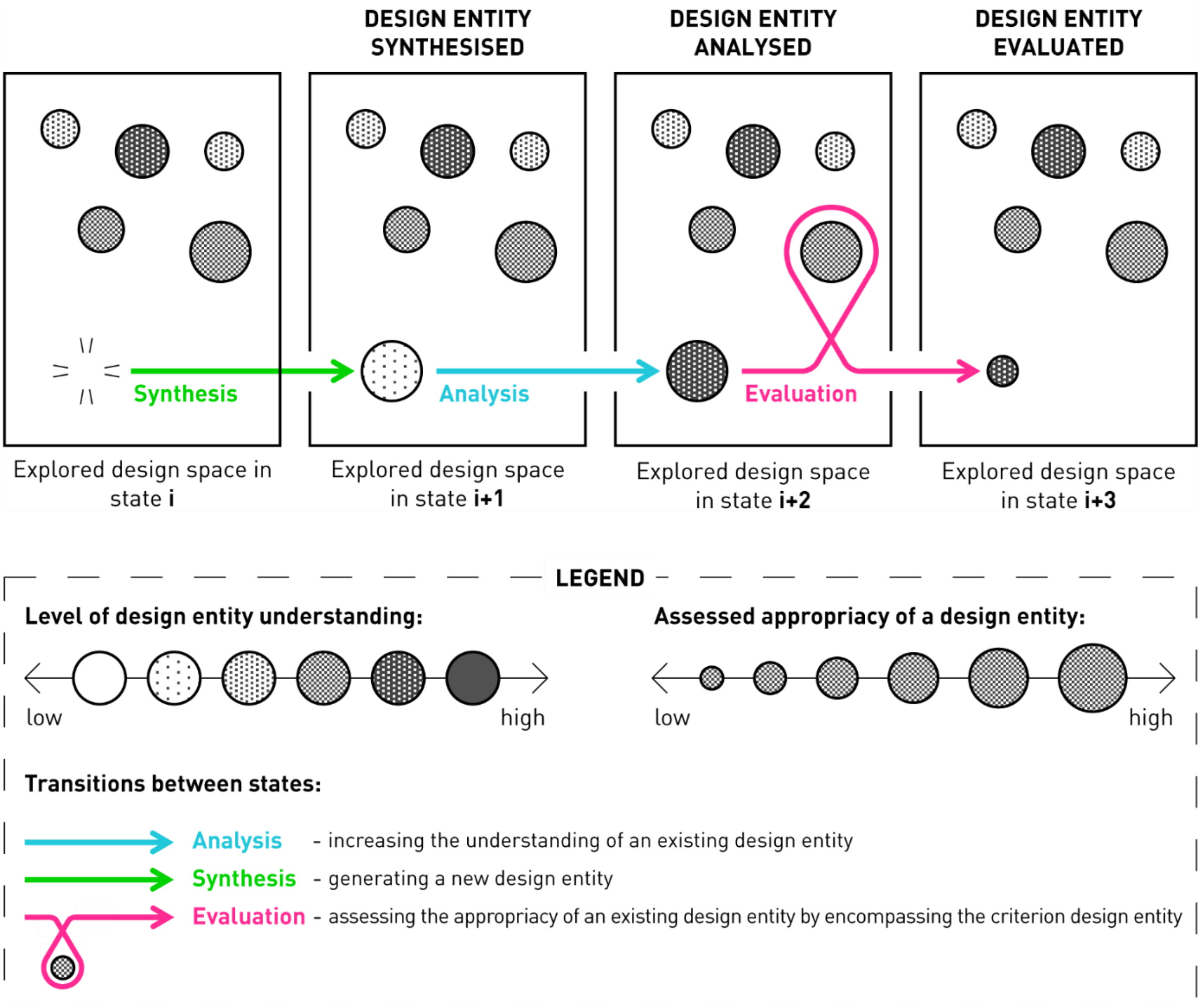

Figure 3.2 Illustration of a state-transition sequence

In state **i** (illustrated in Figure 3.2), the explored design space is likely to be populated with both problem- and solution-related design entities. If members of the design team perform, for example, a synthesis design operation, a new design entity (problem or solution) is revealed (as a result of the transition from state **i** to state **i+1** in Figure 3.2). The new design entity can be either entirely unrelated to existing ones (new or global searches according to Sarkar and

Chakrabarti [225]) or related as an elaboration and improvement of the existing design entities (local and detail searches).

If team members perform analysis design operation, they increase the individual or shared understanding of a design entity (transition from state **i+1** to state **i+2** in Figure 3.2). The aim of analysis can be to improve the understanding of certain aspects of design entities (e.g. to determine the behaviour of a solution, as seen by Gero [211]), or to avoid misunderstanding between team members [54]. The better the design entity is understood, the darker it appears in Figure 3.2 state illustrations.

Finally, as designers progress through conceptual design activity, they require convergent action to narrow down the choices [247], [248]. Designers thus evaluate problems and solutions to distinguish the ones that are reasonable and acceptable. When team members perform evaluation design operation, they asses the appropriacy of a design entity concerning the relevant criteria (the assessed appropriacy of the design entity changes as a result of a transition from state **i+2** to state **i+3** in Figure 3.2). Note that the evaluation design operation does not only affect the assessed design entity, but also encompasses the design entity which serves as the assessment criterion). The reduced or increased size of the design entities in Figure 3.2 illustrates the assessed appropriacy.

Formulation of fundamental differences between analysis, synthesis and evaluations and their effect on changing the state of the explored design space enables straightforward mapping of different information-processing notions available in the reviewed literature (Subsections 2.1.2, 2.2.2. and 2.3.2). The ability to map information-related processes appearing in other studies is essential for inter-study comparison and discussion of insights resulting from the application of the developed model. An overview of the often-used information-processing notions and the associated ASE design operations is shown in Table 3.1.

Table 3.1 Mapping of various information-processing notions from design literature onto ASE design operations as transitions between states

ANALYSIS	**Analyse** [42], [54], [174], [210], [211], [215], [249], [250]; **Simulate** [210], [215], [251]; **Clarify** [54], [56]; **Acquire** [142]; **Calculate** [251]; **Compare** [251]; **Correct** [56]; **Interpret** [142]; **Understand** [159]; **Read** [252]; **Repeat** [252]; **Request** [252];
SYNTHESIS	**Synthesise** [42], [174], [210], [211]; **Generate** [36], [53], [54], [159], [215], [218], [249], [250], [251]; **Define** [41], [222]; **Elaborate** [249], [252]; **Gather** [145], [250]; **Modify** [218], [252]; **Add** [252]; **Create** [41]; **Compose** [215]; **Formulate** [211]; **Model** [250]; **Patch** [251]; **Propose** [252]; **Refine** [251]; **Redefine** [215]; **Select** [251];
EVALUATION	**Evaluate** [41], [42], [53], [54], [159], [174], [210], [211], [218], [250], [251], [252]; **Decide** [41], [54], [159], [250]; **Select** [53], [218]; **Accept** [54], [251]; **Verify** [249]; **Reject** [251]; **Suspend** [251]; **Qualify** [252]; **Justify** [252]

The mapping of information-related processes was performed based on the definitions given in the literature and relating them to the ASE as illustrated in Figure 3.2, that is, whether an entity is created as a result of that micro-level process (synthesis), whether understanding of an entity is increased (analysis), or whether the appropriacy of an entity is assessed (evaluation).

Additionally, a link can be made between the ASE design operations and the co-evolution of concept and knowledge spaces within the C-K theory (to a limited degree, based on [194] and [253]). Namely, any generation of new entities within the concept space ("undecidable" propositions relative to the content of knowledge space) can be attributed to the synthesis design operation. The new entity can either be a result of disjunction (new undecidable propositions are proposed on the basis of decidable propositions, that is using the available knowledge) or refining/choosing/structuring (new concepts are proposed based on undecidable propositions, that is using concept propositions only). On the other hand, generation of new entities within the knowledge space, that is the expansion of knowledge space based on concepts or properties of concepts that have become decidable, can be linked with the evaluation design operation. Finally, the analysis design operation can be associated to the investigation of decidability of a new concept with respect to the knowledge space (identifying the known and unknown properties of a concept design entity) and explorations within the knowledge space (learning, experiments, use of design methods irrespectively of the proposed concepts) when such are needed.

3.2. State-transition model of team design activity

The proposed definitions of ASE design operations fit within the framework presented in Figure 3.1 by matching the transitions between the states of the design space. In addition, a micro-scale design process model has been added to the framework to capture the dynamics of these transitions during a team conceptual design activity. According to McMahon [117], one of the methods suitable for describing fine-grain design process elements such as design operations is state-transition modelling. Hence, the dynamics of the micro-scale design process of team conceptual design activities are here described using a state-transition model. The model visualisation is shown in Figure 3.3.

The state nodes in the model represent the states of the design space after ASE design operations have been performed. Once the design entity has been analysed, the state within the model changes to "design entity analysed", as shown in Figure 3.2 and Figure 3.3. Similarly, the synthesis design operation changes the state to "design entity synthesised" and evaluation to "design entity evaluated".

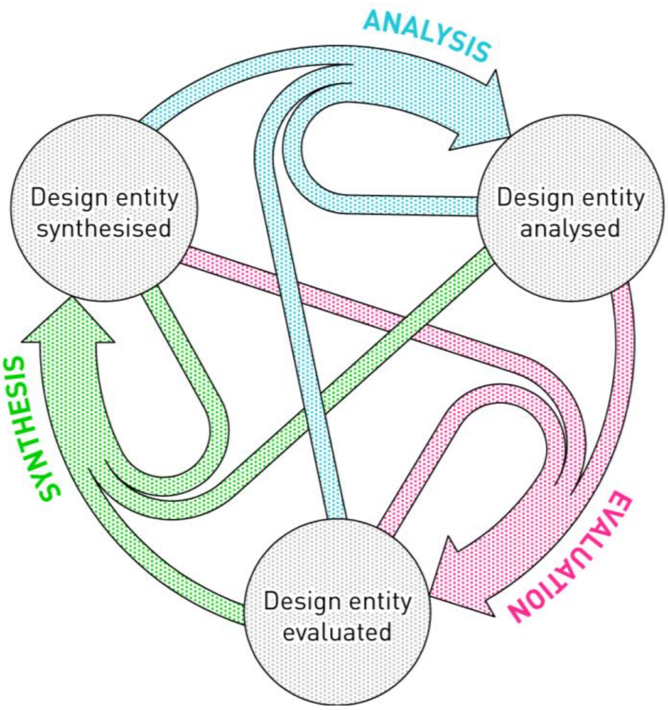

Figure 3.3 State-transition model visualisation illustrating ASE design operations performed within the design space

The model is conceptualised in a way that, when performing an analysis of team design activity, the transitions between the state nodes are assigned with probabilities of being performed by the team and proportions of being performed within a particular period. The probabilities and proportions can be expressed cumulative for the overall activity (based on average probabilities of transitions during the whole activity – see, e.g. Subsections 4.3.1 and 4.3.2), or as they change throughout the activity (see, e.g. Subsection 4.3.3). For example, once team members have synthesised a design entity, they have made a change to the design space. The explored design space is now in the “design entity synthesised” state and the team can carry out further design operations. They can perform analysis, synthesis or evaluation, each with a certain probability assigned within the current state node. If the next step is a synthesis of a new design entity, the transition will return into the same node which will then represent the next state of “design entity synthesised” (now with one new entity). If the team, however, performs analysis or evaluation, the state changes along the corresponding transitions. The change in the state also results with new probabilities of ASE transitions in the following step (e.g. the most probable transition after analysis might be synthesis, but once synthesis is carried out the most probable transition might then be evaluation).

Rather than having a sequential nature, the model’s flexibility allows iterative cycles of a single or several types of design operations. For example, the model can reflect the sequences of ASE design operations driven by divergent (cycles of synthesis) and convergent thinking (cycles of analysis and evaluation) [247], [248], where a single or a pair of design operations dominate. Such descriptions are relevant since new design entities do not appear at a constant pace, nor is every new design entity analysed and evaluated [254].

The model visualised in Figure 3.3 considers design space as one-dimensional (without dividing it to problem and solution space) for the simplicity of representation and clarification. As such, the model consists of three states and nine transitions between these states. Nevertheless, the model can easily be extended to map also ASE transitions within and in-between the problem and the solution space, thus providing additional insight into the co-evolution of these two spaces. In this way, each transition is divided into four subtypes: two within the spaces (solution to solution and problem to problem), and two in-between the spaces (problem to solution and solution to problem). With these four subtypes of transitions, the model gets more complex since the number of possible transitions increases to 36. The visualisation of ASE transitions in both spaces is presented in Figure 3.4. Additional colour codes have been added to highlight transitions within and in-between the problem and the solution space.

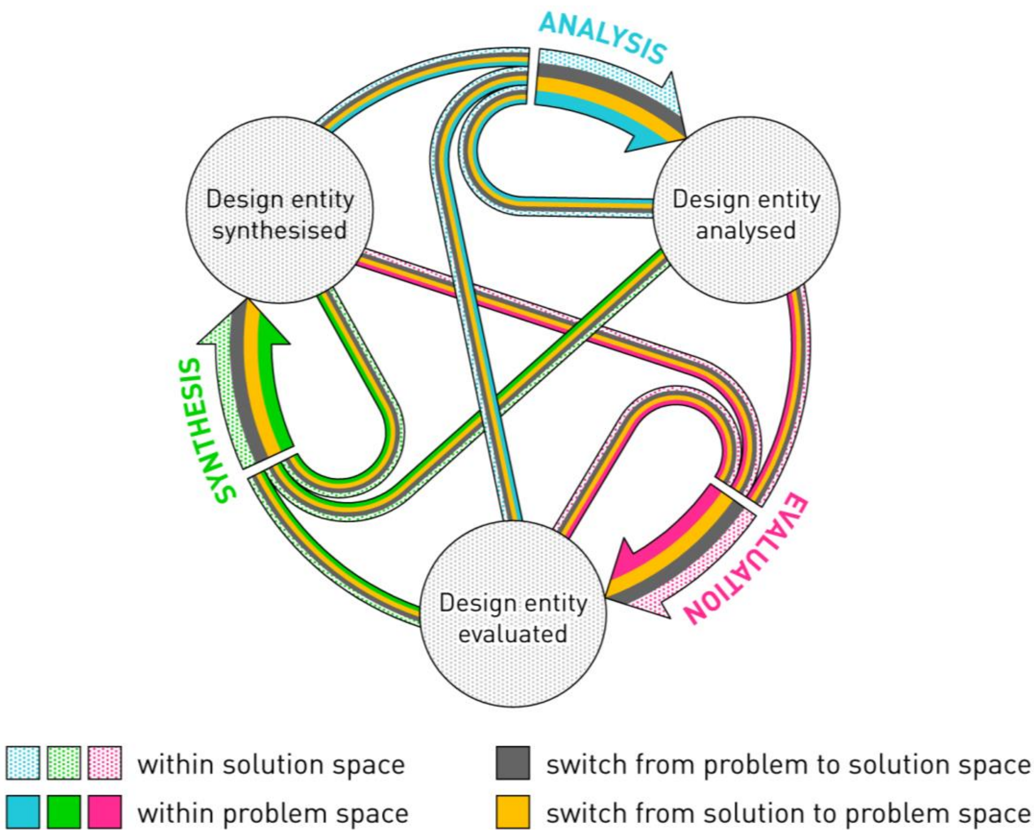

Figure 3.4 State-transition model visualisation illustrating ASE design operations performed within and in-between problem and the solution space

Transitions within the spaces reflect the evolution of a single space (problem or solution), and transitions in-between the spaces reflect how teams switch from one space to another and thus drive the co-evolution of problems and solutions.

The visualisation of the state-transition model can be further enhanced by assigning thickness to the state transition edges (arrows) based on the proportion of ASE design operations during team conceptual design activities. In this manner, the relative thickness of a single transition in comparison to other transitions corresponds to the ratio of the matching design operation and all possible (36) types of design operations during the activity. Experimentally-based examples of visualising the transition proportions are presented as part of the protocol analysis (Chapter 4) and computational experimental studies (Chapter 6).

3.3. Variables and measures

The theoretical model is intended for capturing design operations by means of experimental studies as well as a support for simulating sequences of design operations during team conceptual design activities. Both purposes require identifying and defining the variables of interest, as well as their measures and a reliable and valid manner of measurement [255]. As shown in the research background (Chapter 2), the majority of fine-grain studies of design activity utilise protocol analysis to decompose the process into small chunks (process elements) [23]. The resulting protocols (instances of process elements) are usually analysed in terms of their duration, frequency and sequences, that is the probabilities of moving from one process element to another (for the most relevant examples, please consult [36], [46], [54], [55], [67], [101], [203], [215], [218], [222], [117], [254]). A similar approach is adopted here, and three dependent sets of variables have been defined as follows:

- **Proportions of design operations:** Instances of ASE design operations within the problem and the solution space are counted and normalised (divided by their total number) in order to calculate the proportion of each type of design operation in the time span of the team conceptual design activity (or fragment of the activity). Proportions of design operations (measured in percentages) provide insight into the general information-processing nature of the investigated activity, in terms of the team’s orientation towards analysing, synthesising or evaluating problem and solution entities.
- **Proportions of design operation sequences:** Instances of two or more (depending on the desired degree of analysis) consecutive design operations are counted, and the

overall distribution is normalised to calculate the proportions of different combinations of sequences of two or more design operations. Proportions of design operation sequences enable identification of most common state-transition patterns exhibited when designing in teams. Proportions of design operation sequences are also measured in percentages.

- **Probabilities of design operation sequences:** Proportions of sequences of two design operations can be transformed into probabilities of moving in-between different types of design operations. Probabilities, again measured in percentages, are essential for both comparing and generating of experimental datasets.

Variables related to proportions of design operations are utilised for measuring and modelling of information processing, whereas the variables related to proportions and probabilities of design operation sequences are used for measuring and modelling the patterns of information processing in teams developing technical systems. It is here argued that the relationship between the proportions of ASE design operations and proportions of moves between ASE design operations can be statistically modelled, as shown in Chapter 5.

The reliability of the abovementioned measures [255] must be ensured as part of the data collection methodology. In the case of protocol analysis study reported within Chapter 4, the level of reliability is determined by calculating the inter-rater (inter-coder) reliability [101], [256]. The validity of the selected variables [255] and the overall utility of the proposed framework and model are discussed in Chapter 7. The validity is determined qualitatively, based on the alignment of results with other findings from other studies in the design research field. The purpose of the developed theoretical framework and the state-transition model is to capture, describe and simulate both the common and specific patterns of proportions and sequences of design operations. Following is the depiction of how different scenarios can be modelled via the developed state-transition model.

3.3.1. Proportions of design operations

As shown in the problem and solution space visualisation of the state-transition model (Figure 3.4), the comprehensive measuring of design operations must include ASE design operations within and in-between the problem and the solution space. Hence, when analysing team design activity, it is necessary to capture the appearance of six basic design operations: problem analysis, problem synthesis, problem evaluation, solution analysis, solution synthesis and solution evaluation. These six types can, if necessary, be aggregated into ASE or problem- and solution-related design operations. Hence, if a team conceptual design activity is decomposed into a string containing n instances of design operations, the counted instances can be categorised as shown in Table 3.2.

Table 3.2 Expressions describing numbers of instances and proportions of design operations

	DESIGN OPERATION CATEGORIES	EXPRESSION	
		Number of instances	Proportion
Measured	Problem analysis (PA)	$\boldsymbol{n}_{\mathbf{PA}}$	$\boldsymbol{p}_{\mathbf{PA}} = n_{PA} / n$
	Problem synthesis (PS)	$\boldsymbol{n}_{\mathbf{PS}}$	$\boldsymbol{p}_{\mathbf{PS}} = n_{PS} / n$
	Problem evaluation (PE)	$\boldsymbol{n}_{\mathbf{PE}}$	$\boldsymbol{p}_{\mathbf{PE}} = n_{PE} / n$
	Solution analysis (SA)	$\boldsymbol{n}_{\mathbf{SA}}$	$\boldsymbol{p}_{\mathbf{SA}} = n_{SA} / n$
	Solution synthesis (SS)	$\boldsymbol{n}_{\mathbf{SS}}$	$\boldsymbol{p}_{\mathbf{SS}} = n_{SS} / n$
	Solution evaluation (SE)	$\boldsymbol{n}_{\mathbf{SE}}$	$\boldsymbol{p}_{\mathbf{SE}} = n_{SE} / n$
Aggregated	Analysis (A)	$\boldsymbol{n}_{\mathbf{A}} = n_{PA} + n_{SA}$	$\boldsymbol{p}_{\mathbf{A}} = n_{A} / n$
	Synthesis (S)	$\boldsymbol{n}_{\mathbf{S}} = n_{PS} + n_{SS}$	$\boldsymbol{p}_{\mathbf{S}} = n_{S} / n$
	Evaluation (E)	$\boldsymbol{n}_{\mathbf{E}} = n_{PE} + n_{SE}$	$\boldsymbol{p}_{\mathbf{E}} = n_{E} / n$
	Problem-related (PRO)	$\boldsymbol{n}_{\mathbf{PRO}} = n_{PA} + n_{PS} + n_{PE}$	$\boldsymbol{p}_{\mathbf{PRO}} = n_{PRO} / n$
	Solution-related (SOL)	$\boldsymbol{n}_{\mathbf{SOL}} = n_{SA} + n_{SS} + n_{SE}$	$\boldsymbol{p}_{\mathbf{SOL}} = n_{SOL} / n$
	Total	$\boldsymbol{n}$	$n / n = 100\%$

The symbol n with a category index is used to express the measured number of instances of that specific category, and the symbol p is used to express the proportions of design operations. As shown in Table 3.2, the proportion of a design operation is expressed as the ratio between the number of instances of that particular operation and the total number of instances of all design operations. Symbolically, the proportion of a design operation p_i can be defined as the number of design operation instances n_i divided by the total number of instances n (Equation 3.1).

$$p_i = \frac{n_i}{n} \qquad \text{(Equation 3.1)}$$

3.3.2. Proportions of design operation sequences

Proportions of sequences of design operations correspond to the proportions of transitions between the states of the explored design space, as conceptualised in Figures 3.1-3.4. A sequence can be defined as two or more consecutive instances of individual design operations. The overall number of sequences within a protocol string (a record of all consecutive design operations in an activity) depends on the number of instances included in a sequence. For example, a protocol string with n instances of design operations contains n-1 sequences of two design operations, n-2 sequences of three design operations, etc. The proportion of a particular combination of design operations in a sequence is equal to the ratio of the number of such sequence combinations found in the protocol string and the total number of sequences. An example of possible combinations of sequences of two design operations is shown in Table 3.3. The total number of possible sequence combinations between the six basic design operations is 36, hence only some have been listed in the table. These 36 combinations of moves between two design operations can be aggregated into 9 combinations of moves between analysis, synthesis and evaluation and 4 combinations of moves in-between the problem- and the solution-related design operations, thus providing higher-level process measures.

Table 3.3 Expressions describing numbers of instances and proportions of different combinations of two consecutive design operations

	EXPRESSION	
	Number of instances	**Proportion**
Measured	$n_{PA,PA}$ (from problem analysis to problem analysis)	$p_{PA,PA} = n_{PA,PA} / (n-1)$
	$n_{PA,PS}$	$p_{PA,PS} = n_{PA,PS} / (n-1)$
	$n_{PA,PE}$	$p_{PA,PE} = n_{PA,PE} / (n-1)$
	$n_{PA,SA}$	$p_{PA,SA} = n_{PA,SA} / (n-1)$
	$n_{PA,SS}$	$p_{PA,SS} = n_{PA,SS} / (n-1)$
	$n_{PA,SE}$	$p_{PA,SE} = n_{PA,SE} / (n-1)$
	$n_{PS,PA}$	$p_{PS,PA} = n_{PS,PA} / (n-1)$
	$n_{PS,PS}$	$p_{PS,PS} = n_{PS,PS} / (n-1)$
	$n_{PS,PE}$	$p_{PS,PE} = n_{PS,PE} / (n-1)$
	⋮	
Aggregated	$n_{A,A} = n_{PA,PA} + n_{PA,SA} + n_{SA,PA} + n_{SA,SA}$	$p_{A,A} = n_{A,A} / (n-1)$
	$n_{A,S} = n_{PA,PS} + n_{PA,SS} + n_{SA,PS} + n_{SA,SS}$	$p_{A,S} = n_{A,S} / (n-1)$
	$n_{A,E} = n_{PA,PE} + n_{PA,SE} + n_{SA,PE} + n_{SA,SE}$	$p_{A,E} = n_{A,E} / (n-1)$
	$n_{S,A} = n_{PS,PA} + n_{PS,SA} + n_{SS,PA} + n_{SS,SA}$	$p_{S,A} = n_{S,A} / (n-1)$
	$n_{S,S} = n_{PS,PS} + n_{PS,SS} + n_{SS,PS} + n_{SS,SS}$	$p_{S,S} = n_{S,S} / (n-1)$
	$n_{S,E} = n_{PS,PE} + n_{PS,SE} + n_{SS,PE} + n_{SS,SE}$	$p_{S,E} = n_{S,E} / (n-1)$
	$n_{E,A} = n_{PE,PA} + n_{PE,SA} + n_{SE,PA} + n_{SE,SA}$	$p_{E,A} = n_{E,A} / (n-1)$
	$n_{E,S} = n_{PE,PS} + n_{PE,SS} + n_{SE,PS} + n_{SE,SS}$	$p_{E,S} = n_{E,S} / (n-1)$
	$n_{E,E} = n_{PE,PE} + n_{PE,SE} + n_{SE,PE} + n_{SE,SE}$	$p_{E,E} = n_{E,E} / (n-1)$
	$n_{PRO,PRO} = n_{PA,PA} + n_{PA,PS} + n_{PA,PE} + n_{PS,PA} + n_{PS,PS} + n_{PS,PE} + n_{PE,PA} + n_{PE,PS} + n_{PE,PE}$	$p_{PRO,PRO} = n_{PRO,PRO} / (n-1)$
	$n_{PRO,SOL} = n_{PA,SA} + n_{PA,SS} + n_{PA,SE} + n_{PS,SA} + n_{PS,SS} + n_{PS,SE} + n_{PE,SA} + n_{PE,SS} + n_{PE,SE}$	$p_{PRO,SOL} = n_{PRO,SOL} / (n-1)$
	$n_{SOL,PRO} = n_{SA,PA} + n_{SA,PS} + n_{SA,PE} + n_{SS,PA} + n_{SS,PS} + n_{SS,PE} + n_{SE,PA} + n_{SE,PS} + n_{SE,PE}$	$p_{SOL,PRO} = n_{SOL,PRO} / (n-1)$
	$n_{SOL,SOL} = n_{SA,SA} + n_{SA,SS} + n_{SA,SE} + n_{SS,SA} + n_{SS,SS} + n_{SS,SE} + n_{SE,SA} + n_{SE,SS} + n_{SE,SE}$	$p_{SOL,SOL} = n_{SOL,SOL} / (n-1)$

The n symbol and the assigned transition indexes are used to express the measured number of design operation sequences, whereas p is used to express their proportions. Symbolically, the proportion of moves between two consecutive design operations $p_{i,j}$ can be defined as the number of counted sequences of these two design operations $n_{i,j}$ over the total number of sequences of two design operations n-1 (Equation 3.2). Similarly, the proportion of moves between three consecutive design operations $p_{i,j,k}$ equals the number of three design operations $n_{i,j,k}$ over the total number of sequences of three design operations n-2 (Equation 3.3).

$$p_{i,j} = \frac{n_{i,j}}{n - 1} \qquad \text{(Equation 3.2)}$$

$$p_{i,j,k} = \frac{n_{i,j,k}}{n - 2} \qquad \text{(Equation 3.3)}$$

Experimental studies (Chapters 4 and 6) have shown that analysing sequences of more than three consecutive design operations provides no significant benefits, primarily due to a small number of instances for every possible combination appearing in a team activity time span.

3.3.3. Probabilities of design operation sequences

The probabilities of one design operation following another design operation (i.e. one state transition following another state transition) have been interpreted as probability matrices in Markov processes [257]. The probability matrix (Markov matrix) is a right stochastic matrix – a square matrix used to describe the probabilities of moving from one element in the matrix (in this case a design operation) to all other elements [257]. It is important to note that the common term used to link the elements of a probability matrix is a "transition". However, to reduce the ambiguity when discussing transitions between design operations (transitions of transitions in the proposed model), this term has been replaced with "moves".

First, the total number of moves between pairs of design operations must be counted and entered into the corresponding cells of the matrix. The probability matrix is then computed by normalising the matrix rows (the resulting sum of values in each row of a right stochastic matrix is 1). The matrix thus includes the probabilities of design operation to appear, given the previous design operations. Symbolically, the probability of a design operation j to appear after design operation i can be formulated as the ratio of the proportion of moves between design operations p_{ij} over the proportion of the first design operation p_i (Equation 3.4).

$$Pr(j \mid i) = \frac{p_{i,j}}{p_i} \qquad \text{(Equation 3.4)}$$

The transitions matrices can then be formulated as shown in the tables below. Probability matrix shown in Table 3.4 involves the probabilities of moves between ASE design operations within and in-between the problem and solution space, whereas the matrices shown in Table 3.5 aggregate these probabilities into probabilities of moves in-between analysis, synthesis and evaluation (left), and problem- and solution-related design operations (right).

Table 3.4 Probabilities of moves between two ASE design operations within and in-between problem and solution space, given the previous design operation

FROM ↓ TO →	PA	PS	PE	SA	SS	SE
Problem analysis (PA)	$\frac{p_{PA,PA}}{p_{PA}}$	$\frac{p_{PA,PS}}{p_{PA}}$	$\frac{p_{PA,PE}}{p_{PA}}$	$\frac{p_{PA,SA}}{p_{PA}}$	$\frac{p_{PA,SS}}{p_{PA}}$	$\frac{p_{PA,SE}}{p_{PA}}$
Problem synthesis (PS)	$\frac{p_{PS,PA}}{p_{PS}}$	$\frac{p_{PS,PS}}{p_{PS}}$	$\frac{p_{PS,PE}}{p_{PS}}$	$\frac{p_{PS,SA}}{p_{PS}}$	$\frac{p_{PS,SS}}{p_{PS}}$	$\frac{p_{PS,SE}}{p_{PS}}$
Problem evaluation (PE)	$\frac{p_{PE,PA}}{p_{PE}}$	$\frac{p_{PE,PS}}{p_{PE}}$	$\frac{p_{PE,PE}}{p_{PE}}$	$\frac{p_{PE,SA}}{p_{PE}}$	$\frac{p_{PE,SS}}{p_{PE}}$	$\frac{p_{PE,SE}}{p_{PE}}$
Solution analysis (SA)	$\frac{p_{SA,PA}}{p_{SA}}$	$\frac{p_{SA,PS}}{p_{SA}}$	$\frac{p_{SA,PE}}{p_{SA}}$	$\frac{p_{SA,SA}}{p_{SA}}$	$\frac{p_{SA,SS}}{p_{SA}}$	$\frac{p_{SA,SE}}{p_{SA}}$
Solution synthesis (SS)	$\frac{p_{SS,PA}}{p_{SS}}$	$\frac{p_{SS,PS}}{p_{SS}}$	$\frac{p_{SS,PE}}{p_{SS}}$	$\frac{p_{SS,SA}}{p_{SS}}$	$\frac{p_{SS,SS}}{p_{SS}}$	$\frac{p_{SS,SE}}{p_{SS}}$
Solution evaluation (SE)	$\frac{p_{SE,PA}}{p_{SE}}$	$\frac{p_{SE,PS}}{p_{SE}}$	$\frac{p_{SE,PE}}{p_{SE}}$	$\frac{p_{SE,SA}}{p_{SE}}$	$\frac{p_{SE,SS}}{p_{SE}}$	$\frac{p_{SE,SE}}{p_{SE}}$

Table 3.5 Probabilities of moves between two design operations aggregated to ASE (left) and problem- and solution-related design operations (right)

FROM ↓ TO →	A	S	E
Analysis (A)	$\frac{p_{A,A}}{p_{A}}$	$\frac{p_{A,S}}{p_{A}}$	$\frac{p_{A,E}}{p_{A}}$
Synthesis (S)	$\frac{p_{S,A}}{p_{S}}$	$\frac{p_{S,S}}{p_{S}}$	$\frac{p_{S,E}}{p_{S}}$
Evaluation (E)	$\frac{p_{E,A}}{p_{E}}$	$\frac{p_{E,S}}{p_{E}}$	$\frac{p_{E,E}}{p_{E}}$

FROM ↓ TO →	PRO	SOL
Problem-related (PRO)	$\frac{p_{PRO,PRO}}{p_{PRO}}$	$\frac{p_{PRO,SOL}}{p_{PRO}}$
Solution-related (SOL)	$\frac{p_{SOL,PRO}}{p_{SOL}}$	$\frac{p_{SOL,SOL}}{p_{SOL}}$

Variables describing the proportions of individual design operations and probabilities of moves from one design operation to another are not independent. The probabilities of moves between two design operations are inherited from proportions of individual design operations. For example, the more analysis-intensive an activity is, the higher the probability of moves from either analysis, synthesis or evaluation towards analysis. Nevertheless, the precise relationship between these variables can only be hypothesised at this point. Regression analysis using experimental data sets is needed to determine the type of dependency (linear, polynomial) and the coefficients involved (consult Chapter 5 for more details).

3.3.4. ASE proportion visualisation

In order to characterise the gravitation of design operation proportions towards the analysed, synthesised and evaluated states, the overall state-transition model visualisation can be simplified as a triangular representation of the ASE proportions (Figure 3.5). The triangular proportion visualisation has been colour-coded to emphasise the prevalent design operation type. Thus, for analysis-intensive sequences of design operations, the proportions of ASE gravitate towards the upper right corner of the triangular visualisation. Moreover, synthesis-intensive sequences move the ASE proportions towards the top left, and the evaluation-intensive sequences towards the bottom corner of the triangular proportion visualisation.

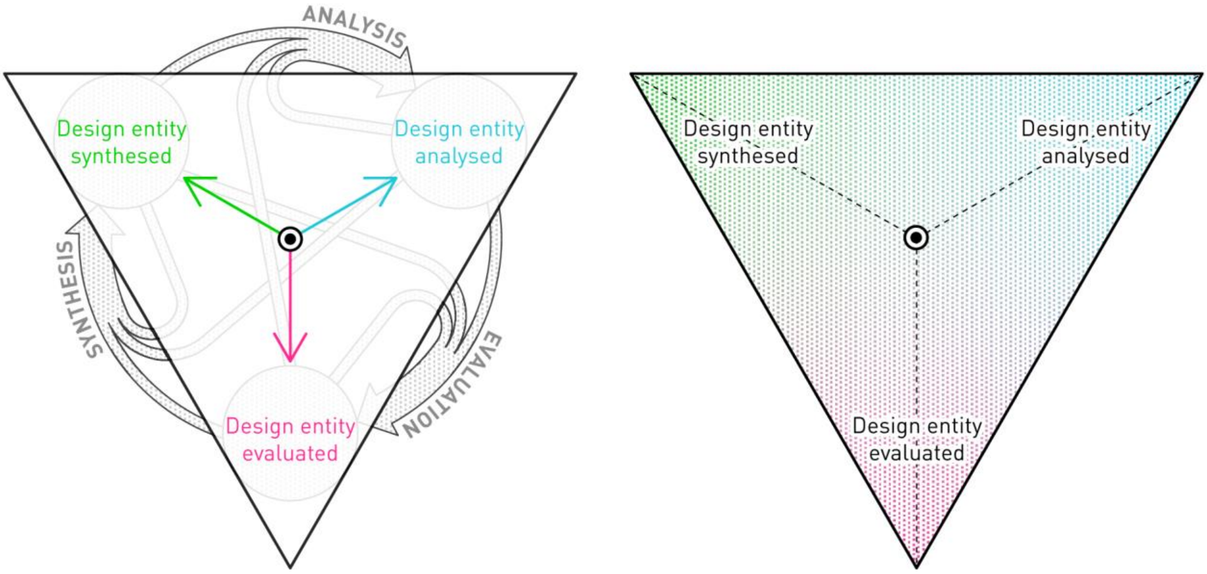

Figure 3.5 Simplified triangular visualisation of design operation proportions in-between different states of design entity manipulation (left); and colour-coded visualisation of prevailing design operations (right)

Since the added up proportions of ASE always make up 100%, only two measures are needed to characterise an activity (the third measure can be deducted, e.g. $p_E = 100\% - p_A - p_S$). If the triangular proportion visualisation is utilised, the two measures are embedded in the vector which is anchored in the centre of the triangle (Figure 3.6). The measures correspond to the vector's endpoint distance from the triangle centre of gravity (vector length r) and the direction of the vector (vector direction angle δ), as shown in Figure 3.6. If the distance R from the centre of gravity to the corners of the triangle is conceptualised as equal to 1 (or 100%), then the vector length r ranges from 0 to a maximum of 1 in the triangle corners, whereas the vector direction δ can be any angle. Furthermore, if the angle δ is defined clockwise from the vertical axis, as shown in Figure 3.6, the relations between the triangular visualisation variables and the proportions of ASE design operations can be defined as shown in Equations 3.5, 3.6 and 3.7.

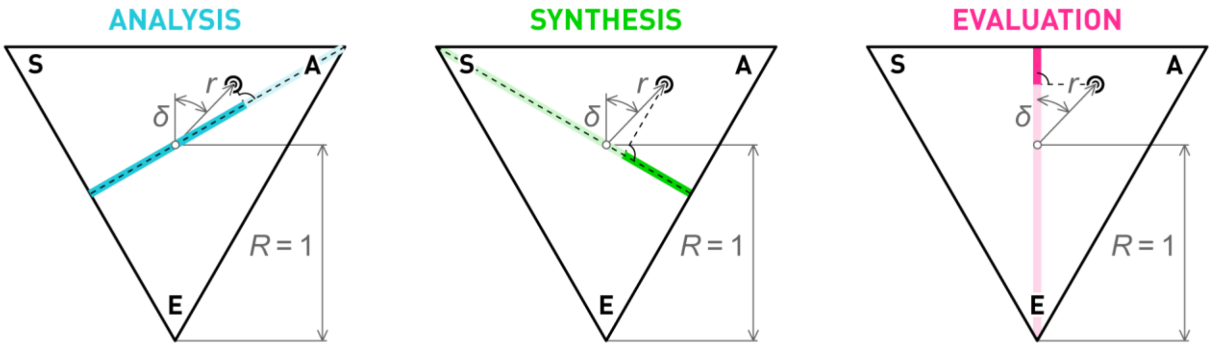

Figure 3.6 Triangular proportion visualisation of ASE design operations using two visualisation variables – distance from the centre of gravity r and angle δ

Equations 3.5-3.7 reveal that, in the case where the vector length is zero, the proportion of all three design operations is equal to 1/3.

$$p_A = \frac{1}{3} + \frac{2}{3} \cdot r \cdot \cos(60° - \delta) \quad \text{(Equation 3.5)}$$

$$p_S = \frac{1}{3} - \frac{2}{3} \cdot r \cdot \sin(\delta - 30°) \quad \text{(Equation 3.6)}$$

$$p_E = \frac{1}{3} - \frac{2}{3} \cdot r \cdot \cos(\delta) \quad \text{(Equation 3.7)}$$

The proposed visualisation does not only enable intuitive and straightforward characterisation activities' nature in terms of ASE but can also be used to describe the change in ASE proportions as a function of time passed within either a single activity or a set of activities performed by the design team. An example of such visualisation is shown in Figure 3.7.

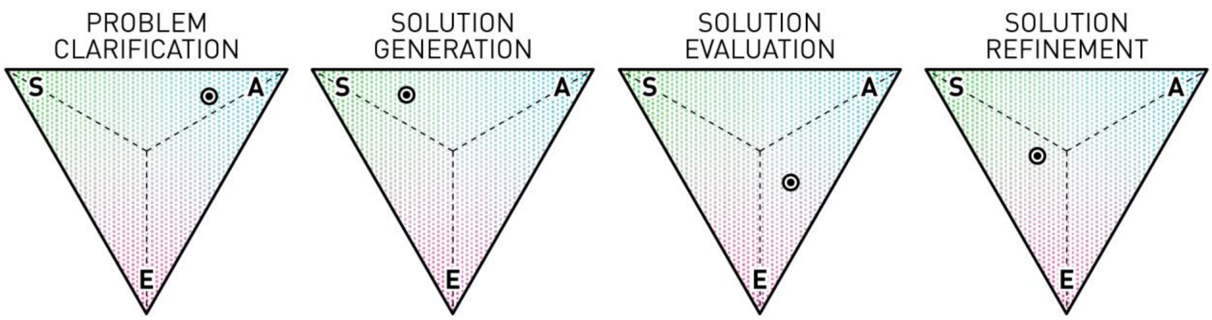

Figure 3.7 An example of changes in ASE proportions during a conceptual design task

The example in Figure 3.7 illustrates the steps of solving a conceptual design task, inspired by the descriptions of the conceptual design stage provided in Table 2.5. The team first clarifies the given problem (analysis intensive), then generates solution alternatives (synthesis), before evaluating the alternatives (analysis and evaluation). Finally, the selected solution is refined (evaluation and synthesis).

Another example of visualising different proportions of ASE and illustrating the hypothesised effect that these proportions have on the proportions of nine transitions between the ASE states of the explored design space is shown in Figure 3.8. The proportions of moves between design operations have been visualised by adjusting the thickness of state-transition edges (arrows).

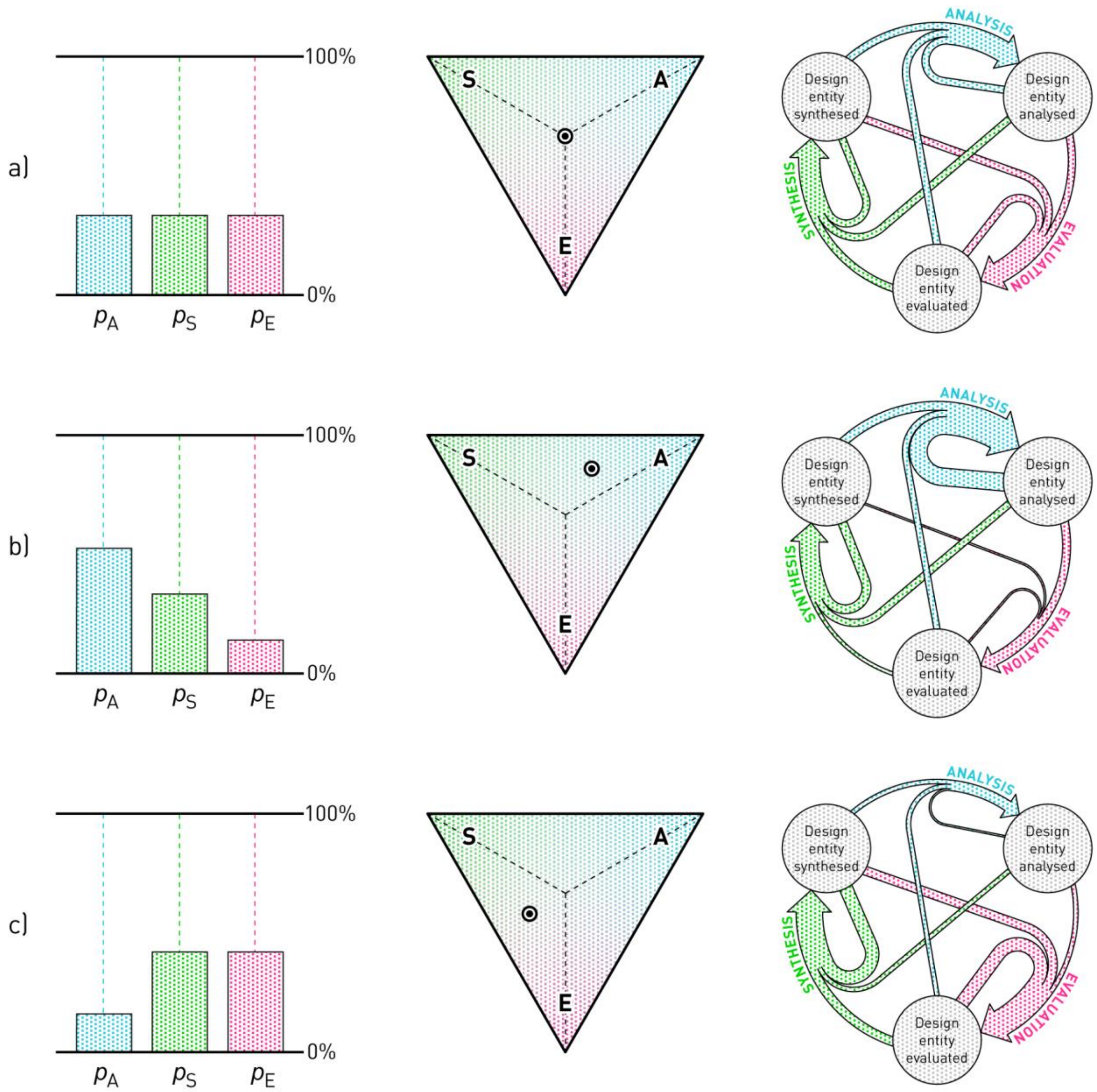

Figure 3.8 Examples of different ASE proportions, their gravitation toward design entity states and visualisation of state transitions: a) p_A=p_S=p_E ; b) p_A>p_S>p_E ; c) p_S=p_E>p_A

A more detailed analysis of proportions can further be performed by assigning ASE design operations to the two spaces: problem and solution space. The analysis of proportions and moves between design operations in one-dimensional design space can be analogously expanded to the problem and the solution space. Hence, the number of proportion variables doubles, as ASE can be measured within both the problem and the solution space. Moreover, the number of possible moves between pairs of ASE design operations within and in-between the problem and the solution space rises to 36 (as shown in Figure 3.4 and Table 3.4). The ASE-related nature of design activities can then be characterised for both spaces. However, it is yet to be investigated if the problem and solution space are likely to exhibit similar proportions and sequences of ASE design operations.

The following three chapters focus on application and further prescriptive development of here presented theoretical framework, particularly concerning the state-transition model and the associated visualisations. Protocol analysis study (Chapter 4) utilises the framework for capturing, analysing and visualising information processing during team ideation and concept review activities. The results of the analysis have then been used for the development of a mathematical model (Chapter 5), that is for modelling the relationships between proportions of individual design operations and the probability of moves in-between different types of design operations. The mathematically formalised relationships are then used to simulate sequences of design operations during team conceptual design in the context of innovative and adaptive design projects (Chapter 6).

4. PROTOCOL ANALYSIS STUDY

The fourth chapter reports on the verbal protocol analysis study of team ideation and concept review activities. First, the experiment setup and the obtained experimental data sets are described. Then the protocol procedure and coding scheme are introduced and employed to capture instances of design operations across the experiment sessions. Finally, the results on proportions and probabilities of design operations and their sequences are presented, and the two activities are compared in order to identify statistically significant differences between team ideation and concept review.

Guided by the studies investigating fine-grain patterns of information processing in team design activity (Section 2.3), the first experimental study has been conducted in the form of verbal protocol analysis. There are several reasons for selecting verbal protocol analysis as the principal means of investigating team conceptual design activity. Firstly, conceptual design communication in design teams is primarily verbal [50], [109]. Secondly, the concern regarding the validity of verbalisations in teamwork is irrelevant, since it is natural for team members to verbally communicate when working together, making verbal data an authentic reflection of real-time thinking in design teams [28]. Thirdly, since the presented research is limited to observing design operations that are exhibited through designers' verbalisations, the segments when designing is not (or cannot be) verbalised are not documented and modelled as the observable information-processing acts in the design process. Studies of gestures, for example, might be prone to lower levels of reliability when compared to verbal protocol analysis (e.g. [258]), or suggest the impracticality of coding designers' facial or postural gesturing [58] and, in the end, often rely on verbalisations (e.g. [259]). Hence, instead of being separately coded, the gestures, mimics, gaze, sketching and other observable aspects can be used for better interpretation of the verbalised information processing, as discussed in the introductory chapter. Finally, as a "third-party observing", protocol analysis can be scientific, independent and relatively objective if it is used to detect the observable aspects of designing [70], [260].

In the light of the research questions RQ2 and RQ3 (Section 2.4), and the developed theoretical framework (Chapter 3), the aim of utilising protocol analysis has been the identification of fine-grain patterns of ASE design operations during team ideation and concept review activities.

Methodologically, the protocol analysis study consisted of three main stages: (1) identifying, obtaining and describing the experimental data set, (2) segmentation and coding, and (3) data analysis and interpretation of the results. The first step was focused on the gathering of experimental data (Section 4.1), namely defining criteria for selecting the appropriate recordings of team conceptual design sessions. In the second step, the recordings of conceptual design sessions were segmented and coded (Section 4.2). The coding scheme for verbal protocol analysis was defined accordingly to the theoretical framework of team conceptual design activity. Lastly, in the final step, the protocol data were analysed and documented (Section 4.3).

4.1. Experimental dataset

Several criteria were considered when identifying the appropriate experimental data set. The recorded experiment sessions should have been collaborative activities, where teams engage in tasks of conceptual design nature. The duration of the task execution should have been relatively short (e.g. no more than two hours) due to the use of protocol analysis method, but long enough to collect a sufficient number of data points. Furthermore, teams should have participated in two different types of activities within the conceptual design stage, to address the research question RQ3.

Video recordings of the two types of team conceptual design activities were obtained from previously conducted studies by Cash et al. [261]. The decision to use existing raw recording data provided several benefits. First, the received data set meets the study requirements, so conducting new experiments could have been avoided. Second, the data set results from a rigorously designed experiment and has already passed several cycles of thorough examination, peer review and publication. Third, studies that used the same raw data set provide additional insights into the design process and offer the potential of coupling the results.

The original experiment structure consisted of four sessions, two of which were conceptualised as team activities – ideation and concept review. The other two experiment sessions were performed by designers individually and are thus not in focus of here presented protocol analysis study. Nevertheless, to provide context for the team sessions, the complete experiment structure is introduced. The instructions given to the participants at the beginning of each experiment session have been aligned with the sequence of specific tasks that designers typically perform throughout the conceptual design stage, as shown in Table 2.4. In particular, each session involved a specific task related to the overall conceptual design problem, that the participants had to solve for the purpose of observation and examination of their design process [262]. The overall conceptual design problem can be formulated as design of a camera-mounting device that can be attached under a helium balloon.

Combining individual and team activity is essential in engineering design. Ulrich and Eppinger explain that team members should spend at least some of their concept generation time working alone, whereas team activities are critical for building consensus, communicating information and refining concepts [139]. Moreover, the practice of divergent ideation, followed by elaboration and integration of ideas, and completed by narrowing and refining ideas is not unique to design, as similar progress can be found across creative group task processes [246]. Hence, the participants were first engaged in an individual information-seeking task. This individual task concerned searching for feasibility-level technical information on camera mounting devices. The individual task was followed by a collaborative ideation activity, in which participants were grouped into teams of three and given a design brief to deliver concept ideas for mounting a camera on a balloon. After the team sessions, participants again worked on individual design tasks to develop a single, elaborated concept. Finally, the teams met again to review and refine the concepts [261].

A total of twelve participants were randomly allocated to four teams. The teams were composed of mechanical engineering students selected from a final year product design and development course. Each participant had an average of 10 months of industrial experience and four years of academic training background at the time of the experiment. For more information on the teams, please consult Cash et al. [261] and Cash and Maier [259].

4.1.1. Ideation activity

During the ideation activity, the teams had 50 minutes to generate as many viable ideas as possible for a camera-mounting concept hanged under a helium balloon. The ideation task brief is shown in Figure 4.1. Before the session, team members have performed an internet search for information that might help to develop a universal camera mount for an aerial vehicle. The concept should have been capable of mounting any camera and orienting it to any point in a hemispherical region. The solution must have been operated remotely. Teams could have recorded their ideas on the whiteboard and sheets of paper. The protocol was based on the participants' natural conversational acts (without imposing any verbalisation requirements), to reduce the effects of observation. For more information, please consult Cash et al. [261].

During this task we would like you to brainstorm ideas to fulfil the following brief. The aim of this task is to generate as many viable ideas as possible within the time available. Please record these ideas on the white-board as they occur but feel free to make additional notes as necessary.

Using the specification provided, develop a variety of concepts capable of mounting any camera, while slung under a helium balloon. The mount must be capable of orientating the camera to any point in a hemi-spherical region underneath the balloon, and must be operated remotely.

Specification:

Total mass of camera and mount	6 kg (must take a range of cameras within weight limits)
Cost (cost price) of the mount	£75
Operational life (per charge)	1.5 hours
Speed of operation – 360º pan	maximum 30 s minimum 10 s
Type of control	via laptop
Range of controller	100 m
Range of rotation	360º by 180º
Volumetric size	200 x 200 x 150 mm
Balloon connection	flexible
Balloon size	spherical

The design for the balloon has already been finalised, and is tolerant of any connection or interface with the camera mount. Although you should try to minimise motion in the mount where possible, you do not need to consider vibration.

Balloon configuration pictures:

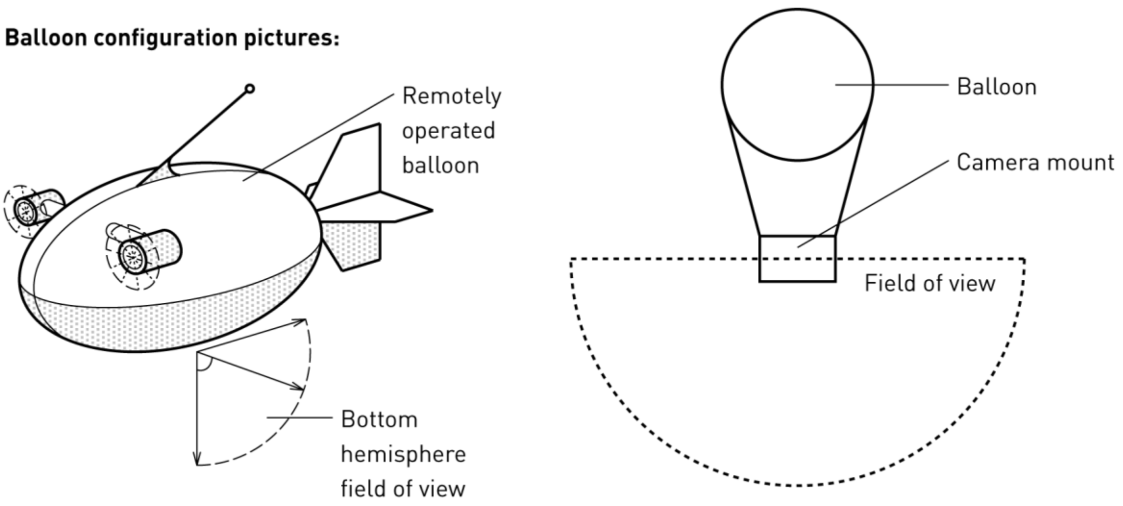

Figure 4.1 Ideation activity task brief (adopted from [263])

4.1.2. Concept review activity

Prior to the concept review activity, team members worked individually on developing detailed concepts of the camera mount. They elaborated their concepts using the additional information on available manufacturing and assembly technologies. Team compositions for the concept review activity were the same as for the ideation activity. During the concept review activity, the teams had 50 minutes to review concepts they developed and elaborated during the individual concept generation task. They were instructed to collaboratively select and develop one, or a combination of concepts and refine them into a final concept solution. The concept review task brief is shown in Figure 4.2. More information can be found in Cash et al. [261].

> During this task we would like you to review your designs (as developed in the previous task). The aim of this task is to select and develop one (or a combination of ideas) into a final concept to be taken forward to production. Please see the following: With your colleagues, and using your developed concepts, select and further develop a single, final concept that best fulfils the brief and specification. Please record this final concept on a single sheet of A3 paper.

Figure 4.2 Concept review activity task brief (adopted from [263])

4.2. Protocol analysis

Protocol coding was conducted using the ELAN software [264] for video annotation (software interface is shown in Figure 4.3). The data set which has been imported within the annotation software consists of 3 separate video recording files per session. Two cameras were oriented towards the experiment participants (team members), and the third one was oriented towards the whiteboard. Experiment participants communicated in English (their native language). A coding scheme has been developed through several iterations of familiarisation with the video recording data set. Once finalised, the coding scheme (see Section 4.2.1) was imported to the annotation software. The final coding scheme and the coding process are explained hereafter.

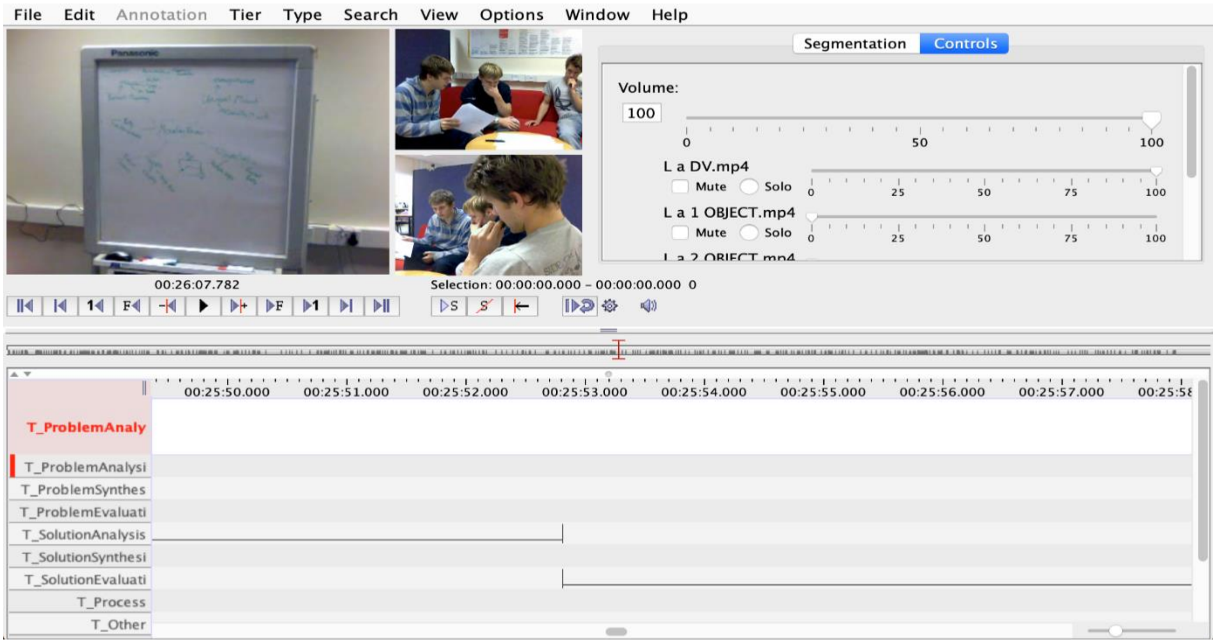

Figure 4.3 Interface of ELAN video annotation software [264] used for protocol coding

The protocols were coded by the primary researcher and a trained coder who was not involved in the development of the theoretical framework. The first (primary) coder coded the entire 50 minutes of the eight experiment sessions. The second (reliability) coder coded random 10 minutes intervals (20% of total session duration) of each experiment session, in order to satisfy the proportion needed for calculating the inter-rater reliability, as suggested by Klonek et al. [265]. Similar approaches to reliability analysis in research of design teams can be seen in the studies of Deken et al. [63], Wiltschnig et al. [67], Eris et al. [58] and Snider et al. [266]. Once the inter-rater reliability was assessed (see Section 4.2.2), all of the identified conflicts were resolved by the two coders, and the final event sequences were agreed.

4.2.1. Coding scheme

As part of the verbal protocol analysis, the recorded team conversations have been transcribed and parsed into coded segments, which were then treated as units of analysis [83], [248]. The transcription process helped to familiarise with the data and to develop and refine the instructions for coding, before performing the final segmentation and coding step. Moreover, two additional codes, "process" and "other", have been recognised and added to the coding scheme in order to capture communicative acts which are not related to the design space. Although the two additional codes have not been considered in here presented analyses (see Section 4.3), they were included in the coding scheme for the convenience of future research using the same experimental data set. The final coding scheme including the results of the inter-rated reliability test (κ_a – explained in detail within the following subsection) are shown in Table 4.1.

The core of the scheme consists of six codes that match the adopted definitions (Chapter 3) of ASE design operations in the problem space (problem analysis, problem synthesis, problem evaluation) and the solution space (solution analysis, solution synthesis, solution evaluation). The "process" code has been intended for coding of discussions concerning the action plan within the session. Detailed process-specific codes were not considered as only a small amount of process-related discussion has been identified. Clear instructions about the design task have been given before sessions start, and there was no need for teams to realign the process often. All remaining communicative acts, such as any off-topic discussion, naming unrelated facts and joking, were coded as "other".

The developed coding scheme was applied to the transcripts of the experiment sessions. The segments were coded following the "one-segment-with-one-code" principle (see [55]). Each segment was assigned with only one of the eight codes based on the coder's critical judgment of recognising ASE design operations as defined in the previous section. Whenever the teams started discussing another design entity or switched the type of design operation performed on the current design entity, a new segment was defined and assigned with the corresponding code. Finally, although the situations in which more than one designer was talking were rare, these segments were coded based on the statement that was more dominant and to which the discussion continued. An example of a segmented and coded transcript is shown in Table 4.2.

Table 4.1 The coding scheme for annotating segments of design team conversation

CODE	DESCRIPTION	CODERS' RELIABILITY (κ_a)
pa: problem analysis	Communicative acts concerning the understanding of problem entities, such as requirements, constraints, specification, user needs, use scenarios, criteria or functions	0.72
ps: problem synthesis	Communicative acts resulting in the appearance of new problem entities	0.78
pe: problem evaluation	Communicative acts concerning the appropriacy assessment of problem entities	0.78
sa: solution analysis	Communicative acts concerning the understanding of solution entities, such as ideas and concept solutions (determining/learning solution entity behaviour, clarifying/building share understanding on the structure of solution entities).	0.70
ss: solution synthesis	Communicative acts resulting in the appearance of new solution entities	0.79
se: solution evaluation	Communicative acts concerning the appropriacy assessment of solution entities	0.78
proc: process	Communicative acts concerning the process of the activity (where to start, how to proceed, etc.)	0.93
o: other	Communicative acts that cannot be annotated with the codes defined above (unrelated facts, joking, off-topic discussion)	0.95

4.2.2. Inter-rater reliability

Since the presented verbal protocol analysis aims to investigate distribution and sequences of design operations, the outputs of the coding are depicted as strings of codes, which are defined by Quera et al. [267] as event sequences. During the coding process, the coders need to identify the events (instances) of analysis, synthesis and evaluation within the problem and the solution space. For this reason, the strings of protocol codes produced by two independent coders may differ in length; that is, the number of coded instances and their alignment are likely to be different. As a consequence, the calculation of Cohen's kappa – the typical approach to assessing the inter-rater reliability – cannot be performed, as it is not clear how the two event sequences can be aligned. A procedure proposed by Quera et al. [267] was utilised to align the protocols and calculate the event-based interpretation of kappa: the event alignment kappa (κ_a). Their procedure essentially utilises routines that are commonly used for finding similarities in DNA sequences to align the two protocol strings, and then calculates the agreement.

Table 4.2 An excerpt of segmenting and coding of experiment transcripts

TIME	PARTICIPANT	SEGMENT TRANSCRIPT	CODE
7:34	P1	[weight restriction concerning the cameras is discussed] *So, we are saying from 200 grams to 3 kilograms…*	ps (new constraint)
7:49	P3	*You then might not be able to attach the full-frame camera…*	pe (constraint evaluated)
7:53	P2	*I think it will be more reasonable to restrict the weight it would lift to a range of decent cameras.*	ps (constraint modified)
8:04	P1	*What about the attachment of the camera?* [requirement introduced earlier in the session]	pa (requirement analysed)
8:10	P1	*The standard camera attachment is this quarter inch threaded screw…*	ss (solution proposed)
8:20	P2	*Screw…? The tripod mount?*	sa (solution clarified)
8:22	P1	*Yes.*	
8:23	P2	*Yeah, that's the thing. Everything has that one… From little compacts right to the big DSLRs*	se (solution evaluated)
8:35	P1	[writing the solution proposal on the whiteboard] *So that is very standard…*	

GSEQ software (see, e.g. [265]) was used to compute the event alignment kappa for each code. Both the overall event alignment kappa value (κ_a=0.71) and the event alignment kappa values for particular codes (reported in Table 4.1) indicate substantial agreement between the two coders. In comparison with other experimental studies in design research (see, e.g. [46], [67], [202]), the agreement has been assessed as adequate for ensuring the research rigour.

4.3. Protocol analysis results

The results are presented in three parts. The first part reveals the proportions of segments assigned with different types of codes during the two experimental sessions, with a particular focus on segments related to design operations. In the second part, the transitions between the coded segments are analysed to identify the sequences of design operations. The ideation and concept review experiment sessions are first examined separately and then compared to determine the significant differences. Finally, the third part reports on the analysis of change in design operation proportions and sequences throughout the sessions. From here on, the experiment sessions will be referred to as ideation and concept review activities.

On average, 333 codes have been coded per team during the ideation activity, and 313 per team during the concept review activity. The discussion related to the problem and the solution space accounts on average for 293 segments per team during the ideation (85-90% of all segments), and for 280 segments per team during the concept review activity (87-92%). The process-related conversation has averaged at 6% during ideation, and at 5% during concept review, and other communicative acts between 5% and 6%. The absolute frequencies of each coded segments and their aggregation to ASE and problem/solution-related design operations during both activities are available in Table 4.3.

Table 4.3 Absolute frequencies of instances of protocol codes during ideation and concept review activities

FREQUENCY VARIABLE	IDEATION						CONCEPT REVIEW					
	T1	**T2**	**T3**	**T4**	**Mean**	**SD**	**T1**	**T2**	**T3**	**T4**	**Mean**	**SD**
Problem analysis (n_{PA})	51	33	44	30	39.50	9.7	21	18	14	16	17.25	3.0
Problem synthesis (n_{PS})	74	47	41	34	49.00	17.5	9	10	14	10	10.75	2.2
Problem evaluation (n_{PE})	23	13	26	13	18.75	6.8	3	5	8	3	4.75	2.4
Solution analysis (n_{SA})	32	70	66	46	53.50	17.8	128	90	132	75	106.25	28.1
Solution synthesis (n_{SS})	72	97	105	99	93.25	14.6	72	71	89	64	74.00	10.6
Solution evaluation (n_{SE})	15	47	59	36	39.25	18.7	81	56	77	53	66.75	14.3
Process (n_{PROC})	25	14	24	16	19.75	5.6	16	18	15	13	15.50	2.1
Other (n_O)	22	24	18	14	19.50	4.4	13	20	26	11	17.50	6.9
Total of all coded segments	**314**	**345**	**383**	**288**	**332.50**	**40.9**	**343**	**288**	**375**	**245**	**312.75**	**57.7**
Analysis (n_A)	83	103	110	76	93.00	16.1	149	108	146	91	123.50	28.6
Synthesis (n_S)	146	144	146	133	142.25	6.2	81	81	103	74	84.75	12.6
Evaluation (n_E)	38	60	85	49	58.00	20.1	84	61	85	56	71.50	15.2
Problem-related (n_{PRO})	148	93	111	77	107.25	30.5	33	33	36	29	32.75	2.9
Solution-related (n_{SOL})	119	214	230	181	186.00	49.1	281	217	298	192	247.00	50.6
Total of ASE in problem and solution space (*n*)	**267**	**307**	**341**	**258**	**293.25**	**38.3**	**314**	**250**	**334**	**221**	**279.75**	**53.1**

T1 ... T4 – Teams 1 to 4; Mean – average of all teams; SD – standard derivation of all teams

The segments related to the design space have been analysed individually (as ASE design operations in the problem and the solution space) but also aggregated into two categories: (1) ASE and (2) problem/solution-related (as proposed within the Chapter 3). The aggregated analysis design operation combines problem and solution analysis (n_{PA}+n_{SA}), the aggregated synthesis design operation combines problem and solution synthesis (n_{PS}+n_{SS}), and the aggregated evaluation design operation combines problem and solution evaluation (n_{PE}+n_{SE}).

Similarly, aggregated design operations within the problem space combine problem analysis, synthesis and evaluation ($n_{PA}+n_{PS}+n_{PE}$), and aggregated design operations in the solution space combine solution analysis, synthesis and evaluation ($n_{SA}+n_{SS}+n_{SE}$).

4.3.1. Observed proportions of design operations

For the purpose of focusing solely on ASE design operations within the problem and the solution space, the segments coded as other- and process-related discussion have been excluded from further analyses (proportion and sequence analyses). Once the "process" and "other" segments were removed, the distribution of counted design operation segments (absolute frequencies, as presented in Table 4.3) was normalised in order to conduct further analyses using proportions (relative frequencies) of design operations. Such normalisation implies that the sum of proportions of all coded design operation segments equals 100%. The resulting proportions for each of the four teams during the two conceptual design activities are shown in Figure 4.4.

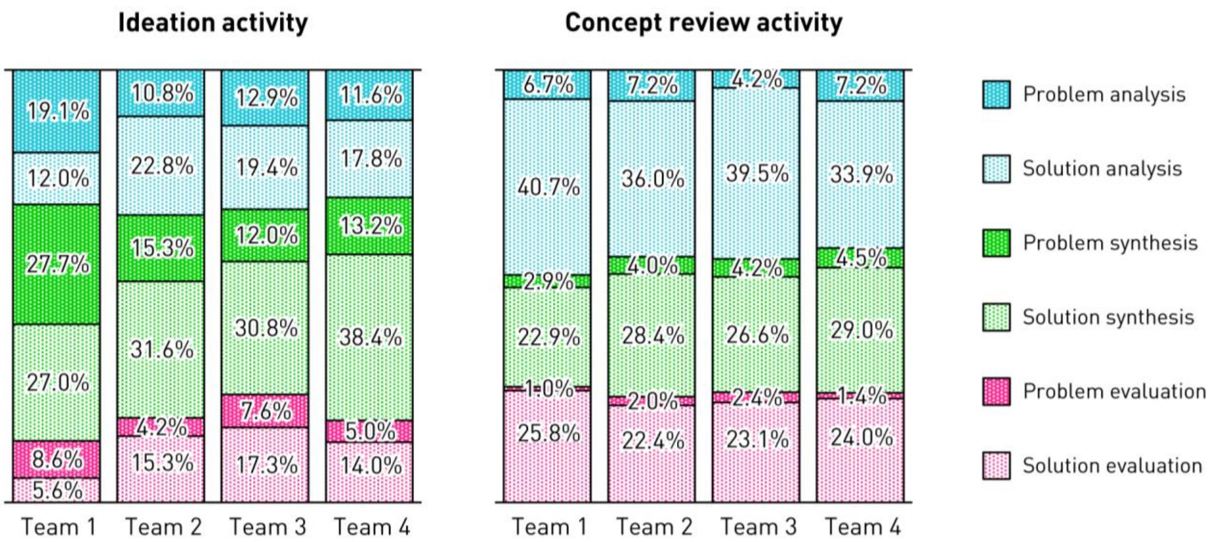

Figure 4.4 Proportions of design operation segments during ideation and concept review activities for all teams

State-transition proportions during ideation activity

During the ideation activity, the most frequent ASE design operation in all four teams was synthesis (on average 49% of all ASE design operations per team), followed by analysis (32%), and evaluation (19%) as the least frequent. Of all design operations, on average 37% were performed in the problem space, and 63% in solution space. One of the teams (Team 1 in Figure 4.4) spent considerably more segments in the problem space (55%) than the other three (30-33%). On average, the most frequent design operation in the problem space was problem synthesis (on average 46% of all design operations in problem space per team), followed by problem analysis (37%) and problem evaluation (17%). Similarly, the most frequent design operation in the solution space was solution synthesis (on average 51% of all design operations in solution space per team), followed by solution analysis (28%) and solution evaluation (21%).

State-transition proportions during concept review activity

The descriptive statistics differ for the concept review activity, where the most frequent ASE design operation was analysis (on average 44% of all ASE design operations per team), followed by synthesis (31%) and evaluation (25%) as the least frequent. Of all design operations, on average 12% were performed in the problem space, and 88% in solution space, which is a considerable change compared to ideation. On average, the most frequent design operation in problem space was problem analysis (on average 53% of all design operations in problem space per team) followed by problem synthesis (33%) and problem evaluation (14%). The order concerning ASE is, again, the same in the solution space: solution analysis was the most frequent design operation in solution space (on average 43% of all design operations in solution space per team), followed by solution synthesis (30%) and solution evaluation (27%).

Differences in state-transition proportions between ideation and concept review activities

A triangular proportion visualisation was developed for qualitative comparison of ASE design operation proportions for each of the teams during the two activity types (Figure 4.5). The visualisation clearly shows that all four teams exhibit similar direction considering the change in overall proportions of ASE design operations. During ideation activity, all teams moderately gravitate towards the synthesis design operation. All teams align their process in the way that the shift in proportions can be visualised as moving towards analysis (right) and evaluation (bottom) within the triangular proportion visualisation.

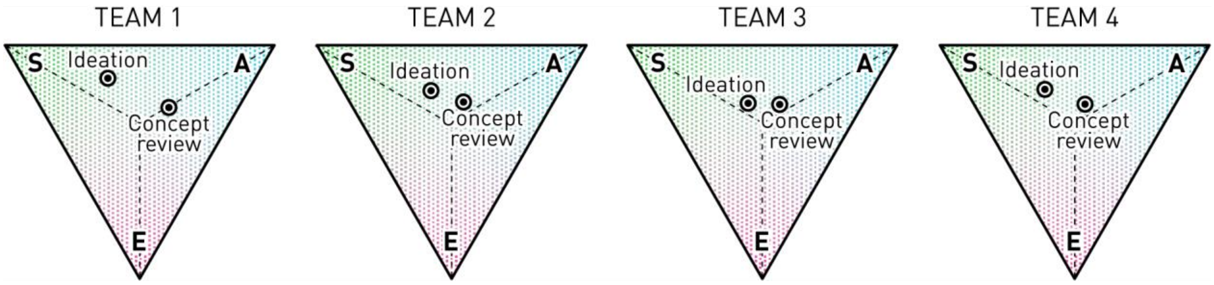

Figure 4.5 Visualisation of differences in ASE proportions between ideation and concept review activities for all teams

Additionally, a two-tailed paired-sample t-test was conducted to compare proportions of design operations separately and aggregated into both ASE and problem-solution space. Results of the test are given in Table 4.4. The normality of design operation distribution has been assumed following a similar approach by Mc Neill et al. [221]. Despite the small sample of teams, significant differences have been identified for the two conceptual design activities.

Table 4.4 T-test comparing proportions of design operations during ideation and concept review activities

PROPORTION VARIABLE	Ideation		Concept review		t value	P value
	Mean (%)	SD (%)	Mean (%)	SD (%)		
Problem analysis (p_{PA})	13.6	3.8	6.3	1.4	3.537	0.038*
Problem synthesis (p_{PS})	17.1	7.2	3.9	0.7	3.319	0.045*
Problem evaluation (p_{PE})	6.4	2.1	1.7	0.6	4.052	0.027*
Solution analysis (p_{SA})	18.0	4.5	37.6	3.1	-5.778	0.010*
Solution synthesis (p_{SS})	31.9	4.7	26.7	2.7	3.661	0.035*
Solution evaluation (p_{SE})	13.0	5.1	23.8	1.5	-3.297	0.046*
Analysis (p_{A})	31.6	1.7	43.9	2.6	-8.593	0.003**
Synthesis (p_{S})	49.0	5.2	30.6	3.4	4.932	0.016*
Evaluation (p_{E})	19.4	4.4	25.5	1.0	-2.442	0.092
Problem-related (p_{PRO})	37.0	12.3	11.9	1.5	3.751	0.033*
Solution-related (p_{SOL})	63.0	12.3	88.1	1.5	-3.751	0.033*

* $p<0.05$ ** $p<0.01$

It is worth noting that the data compared using the t-test embraces not only the effects of transition between ideation and concept review activity in general, but also the effects of other factors such as the specificities of a given design briefs (see, e.g. [262]), effort, fatigue and concentration of experiment participants (see, e.g. [268]), establishment of team identity (changes in stages of team formation; see, e.g. [40]), and other. Hence, although the significant differences in proportions of design operations during ideation and concept review are discussed later in the thesis, there is no certainty that they can be attributed solely to the nature of these two activities.

4.3.2. Observed sequences of design operations

The probabilities of moves in-between all types of design operations, i.e. one state transition following another state transition have been interpreted as probability (Markov) matrices –

square matrices used to describe the probabilities of moving from one element in the matrix (in this case one type of design operation) to all other elements (including the return to the same element, that is the same design operation) [257]. It is here again noted that although a common term used to link the elements of a probability matrix is a “transition”, the term “move” is used to reduce the ambiguity when discussing transitions between design operations (transitions of transitions in the proposed model).

For each of the teams, the total number of moves between pairs of design operations have been counted and entered into the corresponding cells of the matrix. The rows of the matrix were normalised to calculate the probabilities (the sum of values in each row of a right stochastic matrix is 1 or 100%). Each of the resulting matrices represents the probability matrix for that particular team. Probability matrices for all teams during ideation are reported in Table 4.5 and during concept review in Table 4.6. Finally, in order to summarise the data, the probability matrices have been averaged per team. The resulting average probability matrices are shown in Table 4.7. Cells of the matrices have been coloured (heat map) to facilitate identification of moves between design operations that were most likely to appear.

During the ideation activity, the most probable design operation to come after problem analysis was problem synthesis (32.3% probability), after problem synthesis, it was problem analysis (28.9%), and after problem evaluation, it was also problem analysis (33.8%). Furthermore, solution analysis was most likely to be followed by solution synthesis (43.1%), solution synthesis by solution analysis (38.2%), and solution evaluation by solution synthesis (42.3%). As for the aggregated design operations, the most likely moves were as follows: analysis was most likely followed by synthesis (58.3%), synthesis by synthesis (40.5%) or analysis (40.0%), and evaluation by synthesis (54.9%).

During the concept review activity, the most likely moves starting with each of the ASE design operations in problem and solution space were as follows: problem analysis was most likely to be followed by solution synthesis (36.1%), problem synthesis by solution synthesis (34.8%), problem evaluation by solution analysis (46.5%), solution analysis by solutions synthesis (33.4%), solution synthesis by solution analysis (52.4%), and solution evaluation by solution analysis (44.7%). The most likely moves for each of the aggregated ASE design operations were as follows: analysis was most likely to be followed by synthesis (38.8%), synthesis by analysis (53.1%) and evaluation by analysis (53.4%). Please consult Table 4.7 for the probabilities of moves between all pairs of ASE design operations.

Table 4.5 Probability matrices for moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from ideation activity

ASE design operations in problem and solution space / **ASE design operations**

TEAM 1

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.137	0.529	0.176	0.000	0.157	0.000
PS→	0.356	0.329	0.178	0.000	0.137	0.000
PE→	0.391	0.304	0.043	0.000	0.261	0.000
SA→	0.094	0.281	0.000	0.094	0.406	0.125
SS→	0.056	0.083	0.000	0.319	0.389	0.153
SE→	0.067	0.067	0.000	0.400	0.467	0.000

	→A	→S	→E
A→	0.157	0.687	0.157
S→	0.366	0.469	0.166
E→	0.421	0.553	0.026

TEAM 2

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.152	0.333	0.152	0.030	0.333	0.000
PS→	0.149	0.319	0.106	0.064	0.255	0.106
PE→	0.308	0.231	0.077	0.077	0.231	0.077
SA→	0.057	0.129	0.014	0.157	0.386	0.257
SS→	0.093	0.062	0.010	0.423	0.258	0.155
SE→	0.065	0.065	0.000	0.283	0.413	0.174

	→A	→S	→E
A→	0.204	0.563	0.233
S→	0.417	0.403	0.181
E→	0.356	0.475	0.169

TEAM 3

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.182	0.227	0.273	0.023	0.182	0.114
PS→	0.268	0.171	0.244	0.024	0.268	0.024
PE→	0.269	0.308	0.038	0.038	0.346	0.000
SA→	0.077	0.046	0.015	0.077	0.431	0.354
SS→	0.057	0.057	0.019	0.429	0.267	0.171
SE→	0.119	0.119	0.000	0.220	0.339	0.203

	→A	→S	→E
A→	0.174	0.450	0.376
S→	0.432	0.356	0.212
E→	0.329	0.518	0.153

TEAM 4

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.067	0.200	0.167	0.000	0.533	0.033
PS→	0.382	0.206	0.235	0.000	0.176	0.000
PE→	0.385	0.308	0.000	0.077	0.231	0.000
SA→	0.087	0.065	0.000	0.109	0.500	0.239
SS→	0.031	0.061	0.000	0.357	0.337	0.214
SE→	0.083	0.222	0.000	0.139	0.472	0.083

	→A	→S	→E
A→	0.145	0.632	0.224
S→	0.386	0.394	0.220
E→	0.286	0.653	0.061

Table 4.6 Probability matrices for moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from concept review activity

ASE design operations in problem and solution space | **ASE design operations**

TEAM 1

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.143	0.095	0.000	0.238	0.429	0.095
PS→	0.000	0.000	0.222	0.222	0.333	0.222
PE→	0.000	0.000	0.000	0.667	0.000	0.333
SA→	0.063	0.016	0.008	0.242	0.320	0.352
SS→	0.028	0.000	0.000	0.611	0.042	0.319
SE→	0.100	0.063	0.000	0.538	0.200	0.100

	→A	→S	→E
A→	0.315	0.362	0.322
S→	0.593	0.074	0.333
E→	0.639	0.253	0.108

TEAM 2

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.000	0.059	0.118	0.294	0.294	0.235
PS→	0.400	0.000	0.300	0.100	0.100	0.100
PE→	0.400	0.000	0.000	0.400	0.000	0.200
SA→	0.044	0.044	0.000	0.289	0.356	0.267
SS→	0.056	0.014	0.000	0.423	0.324	0.183
SE→	0.071	0.071	0.000	0.446	0.179	0.232

	→A	→S	→E
A→	0.327	0.393	0.280
S→	0.481	0.309	0.210
E→	0.541	0.230	0.230

TEAM 3

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.143	0.071	0.143	0.214	0.286	0.143
PS→	0.214	0.000	0.143	0.071	0.357	0.214
PE→	0.375	0.000	0.000	0.125	0.375	0.125
SA→	0.023	0.038	0.008	0.288	0.379	0.265
SS→	0.011	0.022	0.000	0.539	0.101	0.326
SE→	0.013	0.079	0.039	0.539	0.237	0.092

	→A	→S	→E
A→	0.315	0.411	0.274
S→	0.515	0.155	0.330
E→	0.548	0.321	0.131

TEAM 4

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.000	0.000	0.063	0.500	0.438	0.000
PS→	0.200	0.000	0.100	0.100	0.600	0.000
PE→	0.000	0.000	0.000	0.667	0.000	0.333
SA→	0.053	0.093	0.000	0.227	0.280	0.347
SS→	0.048	0.000	0.000	0.524	0.111	0.317
SE→	0.132	0.057	0.019	0.264	0.434	0.094

	→A	→S	→E
A→	0.319	0.385	0.297
S→	0.534	0.178	0.288
E→	0.411	0.464	0.125

Table 4.7 Probability matrices for moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from ideation and concept review activities (both on average per team)

ASE design operations in problem and solution space								ASE design operations			
		→PA	→PS	→PE	→SA	→SS	→SE		→A	→S	→E
Ideation activity	PA→	0.134	0.323	0.192	0.013	0.301	0.037	A→	0.170	0.583	0.247
	PS→	0.289	0.256	0.191	0.022	0.209	0.033	S→	0.400	0.405	0.195
	PE→	0.338	0.288	0.040	0.048	0.267	0.019	E→	0.348	0.549	0.102
	SA→	0.079	0.130	0.007	0.109	0.431	0.244				
	SS→	0.059	0.066	0.007	0.382	0.313	0.173				
	SE→	0.083	0.118	0.000	0.260	0.423	0.115				
		→PA	→PS	→PE	→SA	→SS	→SE		→A	→S	→E
Concept review activity	PA→	0.071	0.056	0.081	0.312	0.361	0.118	A→	0.319	0.388	0.293
	PS→	0.204	0.000	0.191	0.123	0.348	0.134	S→	0.531	0.179	0.290
	PE→	0.194	0.000	0.000	0.465	0.094	0.248	E→	0.534	0.317	0.148
	SA→	0.046	0.048	0.004	0.261	0.334	0.308				
	SS→	0.036	0.009	0.000	0.524	0.144	0.286				
	SE→	0.079	0.067	0.015	0.447	0.262	0.130				

Probability matrices of individual teams (Table 4.5 and Table 4.6) can be multiplied with the team's corresponding proportion of design operations segments (presented in Figure 4.4) to calculate proportions of particular moves between two design operations for that specific team. The obtained results correspond to the proportions of moves from one ASE design operation to another within the spaces (problem to problem and solution to solution) and in-between the spaces (problem to solution and solution to problem) for a single team. Proportion matrices of all four teams are shown in Table 4.8 for ideation, and in Table 4.9 for concept review activities.

Similar to the average probability matrices, the proportion matrices can be averaged per teams in order to summarise the data. Averaged proportion matrices, which summarise the process of the ideation and concept review activities, are shown in Table 4.10.

Table 4.8 Proportions of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from ideation activity

ASE design operations in problem and solution space | **ASE design operations**

TEAM 1

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.026	0.102	0.034	0.000	0.030	0.000
PS→	0.098	0.090	0.049	0.000	0.038	0.000
PE→	0.034	0.026	0.004	0.000	0.023	0.000
SA→	0.011	0.034	0.000	0.011	0.049	0.015
SS→	0.015	0.023	0.000	0.086	0.105	0.041
SE→	0.004	0.004	0.000	0.023	0.026	0.000

	→A	→S	→E
A→	0.049	0.214	0.049
S→	0.199	0.256	0.090
E→	0.060	0.079	0.004

TEAM 2

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.016	0.036	0.016	0.003	0.036	0.000
PS→	0.023	0.049	0.016	0.010	0.039	0.016
PE→	0.013	0.010	0.003	0.003	0.010	0.003
SA→	0.013	0.029	0.003	0.036	0.088	0.059
SS→	0.029	0.020	0.003	0.134	0.082	0.049
SE→	0.010	0.010	0.000	0.042	0.062	0.026

	→A	→S	→E
A→	0.069	0.190	0.078
S→	0.196	0.190	0.085
E→	0.069	0.092	0.033

TEAM 3

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.024	0.029	0.035	0.003	0.024	0.015
PS→	0.032	0.021	0.029	0.003	0.032	0.003
PE→	0.021	0.024	0.003	0.003	0.026	0.000
SA→	0.015	0.009	0.003	0.015	0.082	0.068
SS→	0.018	0.018	0.006	0.132	0.082	0.053
SE→	0.021	0.021	0.000	0.038	0.059	0.035

	→A	→S	→E
A→	0.056	0.144	0.121
S→	0.185	0.153	0.091
E→	0.082	0.129	0.038

TEAM 4

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.008	0.023	0.019	0.000	0.062	0.004
PS→	0.051	0.027	0.031	0.000	0.023	0.000
PE→	0.019	0.016	0.000	0.004	0.012	0.000
SA→	0.016	0.012	0.000	0.019	0.089	0.043
SS→	0.012	0.023	0.000	0.136	0.128	0.082
SE→	0.012	0.031	0.000	0.019	0.066	0.012

	→A	→S	→E
A→	0.043	0.187	0.066
S→	0.198	0.202	0.113
E→	0.054	0.125	0.012

Table 4.9 Proportions of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from concept review activity

ASE design operations in problem and solution space | **ASE design operations**

TEAM 1

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.010	0.006	0.000	0.016	0.029	0.006
PS→	0.000	0.000	0.006	0.006	0.010	0.006
PE→	0.000	0.000	0.000	0.006	0.000	0.003
SA→	0.026	0.006	0.003	0.099	0.131	0.144
SS→	0.006	0.000	0.000	0.141	0.010	0.073
SE→	0.026	0.016	0.000	0.137	0.051	0.026

	→A	→S	→E
A→	0.150	0.173	0.153
S→	0.153	0.019	0.086
E→	0.169	0.067	0.029

TEAM 2

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.000	0.004	0.008	0.020	0.020	0.016
PS→	0.016	0.000	0.012	0.004	0.004	0.004
PE→	0.008	0.000	0.000	0.008	0.000	0.004
SA→	0.016	0.016	0.000	0.104	0.129	0.096
SS→	0.016	0.004	0.000	0.120	0.092	0.052
SE→	0.016	0.016	0.000	0.100	0.040	0.052

	→A	→S	→E
A→	0.141	0.169	0.120
S→	0.157	0.100	0.068
E→	0.133	0.056	0.056

TEAM 3

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.006	0.003	0.006	0.009	0.012	0.006
PS→	0.009	0.000	0.006	0.003	0.015	0.009
PE→	0.009	0.000	0.000	0.003	0.009	0.003
SA→	0.009	0.015	0.003	0.114	0.150	0.105
SS→	0.003	0.006	0.000	0.144	0.027	0.087
SE→	0.003	0.018	0.009	0.123	0.054	0.021

	→A	→S	→E
A→	0.138	0.180	0.120
S→	0.159	0.048	0.102
E→	0.138	0.081	0.033

TEAM 4

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.000	0.000	0.005	0.036	0.032	0.000
PS→	0.009	0.000	0.005	0.005	0.027	0.000
PE→	0.000	0.000	0.000	0.009	0.000	0.005
SA→	0.018	0.032	0.000	0.077	0.095	0.118
SS→	0.014	0.000	0.000	0.150	0.032	0.091
SE→	0.032	0.014	0.005	0.064	0.105	0.023

	→A	→S	→E
A→	0.132	0.159	0.123
S→	0.177	0.059	0.095
E→	0.105	0.118	0.032

Table 4.10 Averaged proportions of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from ideation and concept review activities

ASE design operations in problem and solution space — **Ideation activity**

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.018	0.048	0.026	0.002	0.038	0.005
PS→	0.051	0.047	0.031	0.003	0.033	0.005
PE→	0.022	0.019	0.002	0.003	0.018	0.001
SA→	0.014	0.021	0.002	0.020	0.077	0.046
SS→	0.018	0.021	0.002	0.122	0.099	0.056
SE→	0.011	0.016	0.000	0.031	0.053	0.018

ASE design operations — **Ideation activity**

	→A	→S	→E
A→	0.054	0.184	0.079
S→	0.195	0.200	0.095
E→	0.066	0.106	0.022

ASE design operations in problem and solution space — **Concept review activity**

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.004	0.003	0.005	0.020	0.023	0.007
PS→	0.009	0.000	0.007	0.004	0.014	0.005
PE→	0.004	0.000	0.000	0.007	0.002	0.004
SA→	0.017	0.017	0.002	0.099	0.126	0.116
SS→	0.010	0.003	0.000	0.139	0.040	0.076
SE→	0.019	0.016	0.003	0.106	0.062	0.030

ASE design operations — **Concept review activity**

	→A	→S	→E
A→	0.140	0.170	0.129
S→	0.162	0.057	0.088
E→	0.136	0.081	0.037

Moreover, the average proportion matrices have been mapped onto the state-transition model proposed in Figure 3.4, by adjusting the thickness of the transition arrows. The resulting visualisations (Figure 4.6 – team level for ideation; Figure 4.7 – team level for concept review; Figure 4.8 – average for both activities) reflect the average proportional distribution of sequences of design operations throughout the ideation and the concept review activities.

Visualisations of state transitions have been developed to qualitatively compare the micro-scale design processes of teams engaged in ideation and concept review activities. Unlike the proportions of design operations presented in Table 4.4, the state-transition model visualisations provide additional insights on what design operations are likely to follow once a problem or solution entity has been analysed, synthesised or evaluated (visualisation of data presented across Tables 4.5-4.10). Additionally, the overall thickness of the arrows entering the state nodes reflects the proportion of analysis, synthesis and evaluation during the activities.

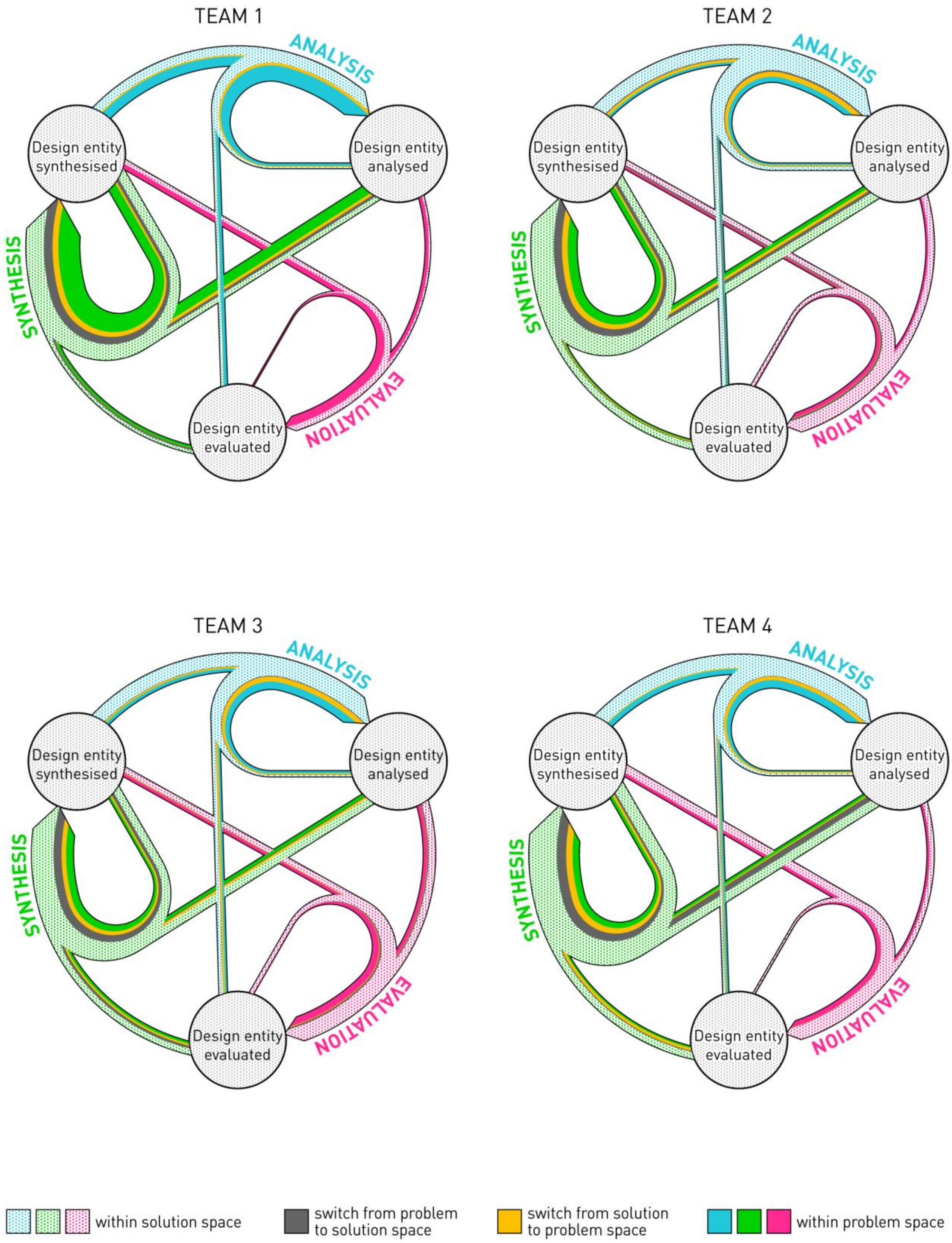

Figure 4.6 State-transition visualisation of proportions of sequences of ASE design operations within and in-between problem and the solution space for all teams during ideation activity

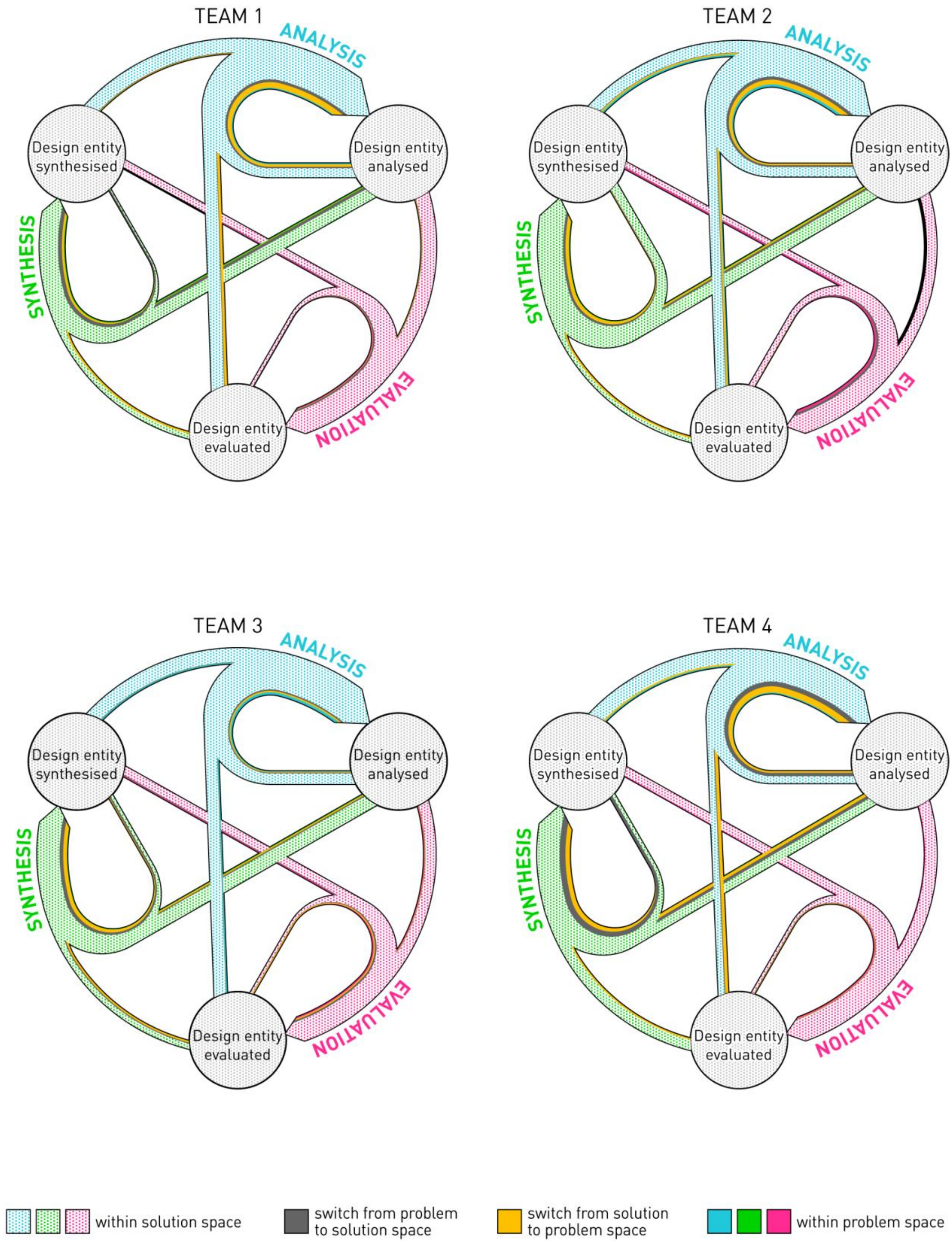

Figure 4.7 State-transition visualisation of proportions of sequences of ASE design operations within and in-between problem and the solution space for all teams during concept review activity

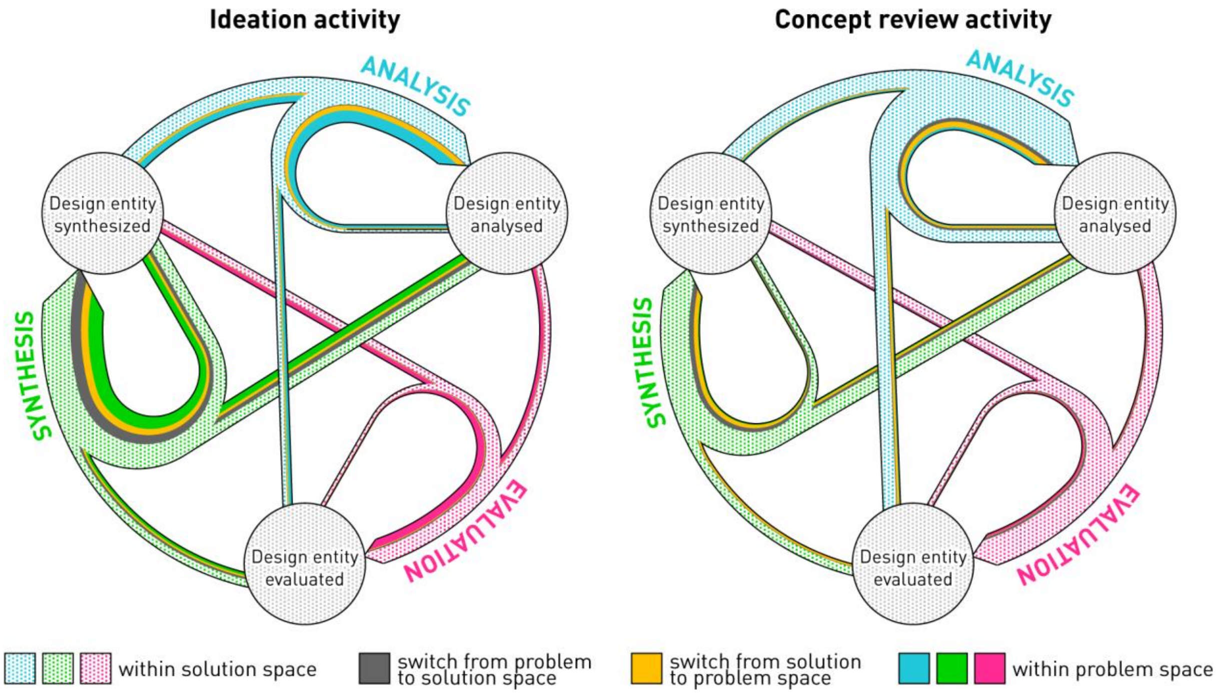

Figure 4.8 State-transition visualisation of average proportions of sequences of ASE design operations within and in-between problem and the solution space during ideation (left) and concept review (right) activity

The visualisations provide qualitative insights into:

- Traces of ASE performed within the problem space (continuous evolution of the problem space)
- Traces of ASE performed within the solution space (continuous evolution of the solution space)
- Traces of ASE performed to switch from problem to solution space, and from solution to problem space (co-evolution of the problem and the solution space)

In addition to the sequences of two design operations, the last part of sequence analysis includes the sequences of three consecutive design operations. Hence, instances of three design operations were counted and normalised for each of the teams, thus providing proportions of particular moves between three design operations. The resulting proportions were averaged across all teams (Table 4.11).

Sequences of three design operations should facilitate identification of patterns related to performing ASE design operations in the problem and the solution space. Nevertheless, mapping the proportions of sequences of three or more design operations onto the state-transition model results in visualisation identical to those shown in Figure 4.8.

Table 4.11 Averaged proportions of sequences of three consecutive design operations obtained from ideation and concept review activities

Ideation activity

	→PA	→PS	→PE	→SA	→SS	→SE
PA→PA→	0.004	0.007	0.003	0.000	0.003	0.002
PA→PS→	0.015	0.014	0.011	0.001	0.006	0.000
PA→PE→	0.008	0.009	0.000	0.001	0.008	0.001
PA→SA→	0.001	0.000	0.000	0.000	0.001	0.000
PA→SS→	0.002	0.000	0.000	0.012	0.016	0.009
PA→SE→	0.000	0.000	0.000	0.002	0.001	0.001
PS→PA→	0.006	0.023	0.009	0.000	0.013	0.001
PS→PS→	0.018	0.022	0.003	0.000	0.004	0.002
PS→PE→	0.011	0.008	0.003	0.002	0.009	0.000
PS→SA→	0.000	0.000	0.000	0.002	0.001	0.001
PS→SS→	0.002	0.003	0.000	0.012	0.009	0.008
PS→SE→	0.001	0.000	0.000	0.002	0.002	0.001
PE→PA→	0.003	0.006	0.006	0.000	0.006	0.000
PE→PS→	0.006	0.004	0.004	0.001	0.003	0.000
PE→PE→	0.001	0.001	0.000	0.000	0.001	0.000
PE→SA→	0.000	0.001	0.001	0.000	0.001	0.000
PE→SS→	0.002	0.001	0.000	0.010	0.005	0.001
PE→SE→	0.000	0.000	0.000	0.000	0.001	0.000
SA→PA→	0.001	0.005	0.005	0.000	0.003	0.000
SA→PS→	0.005	0.003	0.003	0.001	0.009	0.000
SA→PE→	0.001	0.001	0.000	0.000	0.000	0.000
SA→SA→	0.000	0.000	0.001	0.005	0.006	0.009
SA→SS→	0.003	0.007	0.000	0.028	0.027	0.012
SA→SE→	0.003	0.005	0.000	0.008	0.020	0.009
SS→PA→	0.003	0.003	0.002	0.001	0.010	0.001
SS→PS→	0.003	0.002	0.006	0.000	0.006	0.003
SS→PE→	0.001	0.001	0.000	0.000	0.001	0.000
SS→SA→	0.012	0.016	0.000	0.009	0.059	0.026
SS→SS→	0.004	0.007	0.001	0.041	0.027	0.018
SS→SE→	0.004	0.009	0.000	0.012	0.026	0.004
SE→PA→	0.002	0.002	0.002	0.001	0.004	0.001
SE→PS→	0.004	0.002	0.004	0.001	0.005	0.000
SE→PE→	0.000	0.000	0.000	0.000	0.000	0.000
SE→SA→	0.001	0.004	0.000	0.004	0.010	0.011
SE→SS→	0.007	0.002	0.001	0.019	0.016	0.009
SE→SE→	0.003	0.002	0.000	0.007	0.003	0.002

Concept review

	→PA	→PS	→PE	→SA	→SS	→SE
PA→PA→	0.000	0.001	0.001	0.002	0.000	0.000
PA→PS→	0.000	0.000	0.002	0.000	0.001	0.001
PA→PE→	0.002	0.000	0.000	0.000	0.002	0.001
PA→SA→	0.002	0.001	0.000	0.004	0.007	0.007
PA→SS→	0.002	0.000	0.000	0.010	0.006	0.005
PA→SE→	0.001	0.001	0.000	0.003	0.002	0.001
PS→PA→	0.001	0.000	0.001	0.003	0.004	0.000
PS→PS→	0.000	0.000	0.000	0.000	0.000	0.000
PS→PE→	0.002	0.000	0.000	0.005	0.000	0.001
PS→SA→	0.000	0.000	0.000	0.000	0.003	0.002
PS→SS→	0.001	0.001	0.000	0.007	0.000	0.005
PS→SE→	0.000	0.000	0.000	0.003	0.002	0.001
PE→PA→	0.000	0.001	0.001	0.000	0.002	0.001
PE→PS→	0.000	0.000	0.000	0.000	0.000	0.000
PE→PE→	0.000	0.000	0.000	0.000	0.000	0.000
PE→SA→	0.000	0.000	0.000	0.002	0.001	0.003
PE→SS→	0.000	0.000	0.000	0.002	0.000	0.001
PE→SE→	0.001	0.001	0.000	0.001	0.000	0.001
SA→PA→	0.002	0.002	0.000	0.006	0.005	0.003
SA→PS→	0.006	0.000	0.004	0.002	0.006	0.000
SA→PE→	0.001	0.000	0.000	0.000	0.000	0.001
SA→SA→	0.004	0.006	0.000	0.030	0.034	0.024
SA→SS→	0.001	0.001	0.000	0.068	0.018	0.039
SA→SE→	0.009	0.006	0.002	0.050	0.036	0.011
SS→PA→	0.000	0.000	0.000	0.003	0.004	0.003
SS→PS→	0.001	0.000	0.000	0.001	0.001	0.000
SS→PE→	0.000	0.000	0.000	0.000	0.000	0.000
SS→SA→	0.008	0.006	0.000	0.033	0.043	0.049
SS→SS→	0.001	0.001	0.000	0.020	0.010	0.009
SS→SE→	0.005	0.005	0.002	0.038	0.018	0.007
SE→PA→	0.001	0.000	0.002	0.006	0.009	0.000
SE→PS→	0.002	0.000	0.002	0.002	0.007	0.004
SE→PE→	0.000	0.000	0.000	0.002	0.001	0.001
SE→SA→	0.004	0.004	0.002	0.030	0.037	0.030
SE→SS→	0.005	0.000	0.000	0.034	0.007	0.017
SE→SE→	0.003	0.003	0.000	0.013	0.004	0.009

State-transition sequences during ideation activity

The averaged proportions of moves between ASE design operations during the ideation activity (Figure 4.8 on the left, based on Table 4.10) reveal several similarities in performing analysis, synthesis and evaluation within the problem and solution space. The most frequent sequences of two design operations within both spaces were synthesis to synthesis, synthesis to analysis and analysis to synthesis. The decreasing order of the remaining moves in both spaces was: synthesis to evaluation, analysis to evaluation, evaluation to analysis, analysis to analysis, and evaluation to evaluation. Nevertheless, the proportion of moves in problem and solution space differs largely in the case of the evaluation to synthesis sequence, which appeared primarily within the solution space.

Examination of three subsequent design operations (Table 4.11) reveals the most frequent sequences within the problem space: synthesis - analysis - synthesis (on average 2.3% of all sequences) and synthesis - synthesis - synthesis (2.2%); and within the solution space: synthesis - analysis - synthesis (5.9%) and synthesis - synthesis - analysis (4.1%).

Further insights can be derived from Table 4.10 and Figure 4.8. Regarding the moves from one space to another, teams would switch from solution to problem space mainly to perform problem synthesis (on average 5.8% of all moves per team), and problem analysis (4.3%). On average, the most frequent moves from solution to problem space were from solution analysis and solution synthesis to problem synthesis (both 2.1%), followed by moves from solution synthesis to problem analysis (1.8%) and solution evaluation to problem synthesis (1.6%). Only a few instances have been identified where teams switched the space to evaluate a problem (0.4% in total). As for the opposite direction, when switching to the solution space, teams did it primarily to synthesise solutions (on average 8.9% of all moves per team), and rather less frequently to evaluate (1.1%) or analyse (0.8%) solutions. Hence, problem analysis, synthesis and evaluation were all most likely to be followed by solution synthesis when the space was switched.

Nevertheless, the probabilities of moves during the ideation activity (Table 4.7) show that once the teams switched from problem to solution space or vice versa, it was very likely that the next few transitions will remain in that space, before switching spaces again. Thus, the adding up of proportions of design operation moves presented in Table 4.10 shows that on average 52.4% of the moves took place within the solution space, 26.4% within the problem space, and 21.2% in-between the spaces. The most frequent sequence of three design operations which led to switching from problem to solution space was: problem synthesis - problem analysis - solution synthesis (on average 1.3% of all sequences). Similarly, the other way around it was: solution synthesis - solution analysis - problem synthesis (1.6%). Please consult Table 4.11 for a detailed proportional overview for sequences of three design operations.

State-transition sequences during concept review activity

The observed proportions of sequences of ASE design operations during concept review activity differ substantially in comparison to ideation (Figure 4.8 on the right, based on Table 4.10). For the most part, when the teams switched from solution to problem space during concept review, according to Table 4.7, it was unlikely that the next transitions would again be performed within the problem space. In contrast, when they switched from problem to solution space, it was likely for a larger number of solution-related design operations to follow. Thus, on average 79.5% of the design operation moves took place within the solution space and only 3.2% within the problem space, with 17.3% of moves in-between the problem and the solution space.

Consequently, as shown in Table 4.10 and Figure 4.8, the most frequent sequences of two design operations during concept review appeared solely within the solution space. These are, in decreasing order: synthesis to analysis (on average 13.9% of all moves per team), analysis to synthesis (12.6%), analysis to evaluation (11.6%), evaluation to analysis (10.6%) and analysis to analysis (9.9%). The most frequent sequences within the problem space were from synthesis to analysis (0.9%) and from synthesis to evaluation (0.7%). No moves from synthesis to synthesis, evaluation to synthesis and evaluation to evaluation have been identified within the problem space. Interestingly, such moves were also the least frequent within the solution space.

Further examination reveals that the most frequent sequences of three design operations (Table 4.11) within the solution space were analysis - synthesis - analysis (on average 6.8% of all sequences), analysis - evaluation - analysis (5.0%), and synthesis - analysis - evaluation (4.9%). As expected, due to the low proportion of problem-related moves, no frequent sequences of three design operations within the problem space can be singled out.

Teams most frequently switched from solution to problem space in order to analyse existing problems (on average 4.6% of all moves per team) or to synthesise new ones (3.6%). As shown in Table 4.10, these moves most often followed after solution evaluation and solution analysis. The other way around, teams frequently switched from problem space to solution space in order to perform solution synthesis (3.9%). For example, both problem analysis and problem synthesis were most frequently followed by synthesis of solutions once the space was switched.

The most frequent sequences of three design operations which led to switching from problem to solution space were: problem synthesis - problem evaluation - solution analysis (0.5% of all sequences), and problem synthesis - problem analysis - solution synthesis (0.4%). The most frequent sequence from solution to problem space was solution analysis - solution evaluation - problem analysis (0.9%, see Table 4.11 for a detailed overview of sequences).

Differences in state-transition sequences between ideation and concept review activities

The significant differences in the probabilities of moves between design operations during ideation and concept review activities have been identified by performing a two-tailed paired-sample t-test on the probability matrices derived for each team (Tables 4.5 and 4.6). Due to a relatively large number (36) of possible sequences of two design operations, only the sequences of significantly different probabilities are shown in Table 4.12.

Table 4.12 T-test comparing probabilities of design operation moves during ideation and concept review activities

Design operation sequence probability	Ideation		Concept review		t value	P value
	Mean	SD	Mean	SD		
Pr (PS | PA)	0.323	0.149	0.056	0.041	-3.438	0.022*
Pr (PE | PA)	0.192	0.055	0.081	0.063	-2.649	0.034*
Pr (SA | PA)	0.013	0.016	0.312	0.130	4.559	0.023*
Pr (PS | PS)	0.256	0.080	0.000	0.000	-6.426	0.008**
Pr (PS | PE)	0.288	0.038	0.000	0.000	-15.163	0.001**
Pr (SE | PE)	0.019	0.038	0.248	0.103	4.150	0.032*
Pr (PA | SA)	0.079	0.016	0.046	0.017	-2.824	0.030*
Pr (SA | SA)	0.109	0.035	0.261	0.032	6.487	0.005**
Pr (PS | SS)	0.066	0.012	0.009	0.011	-7.003	0.012*
Pr (SE | SS)	0.173	0.029	0.286	0.069	3.031	0.037*
Pr (SA | SE)	0.260	0.110	0.447	0.129	2.195	0.025*
Pr (A | A)	0.170	0.026	0.319	0.006	11.338	0.001*
Pr (S | A)	0.583	0.102	0.388	0.020	-3.747	0.049*
Pr (A | S)	0.400	0.030	0.531	0.047	4.728	0.038*
Pr (S | S)	0.405	0.047	0.179	0.097	-4.194	0.036*
Pr (E | S)	0.195	0.026	0.290	0.057	3.040	0.050
Pr (A | E)	0.348	0.057	0.534	0.094	3.404	0.003**
Pr (S | E)	0.549	0.076	0.317	0.106	-3.571	0.003**

* p<0.05   ** p<0.01

Out of 36 possible sequences of two design operations, 11 have been found to significantly differ in their probability when comparing ideation to concept review activity (Table 4.12).

One-tailed paired-sample t-test further reveals that the probabilities of design operation sequences directed towards the problem space (problem analysis to problem synthesis, problem analysis to problem evaluation, problem synthesis to problem synthesis, problem evaluation to problem synthesis, solution analysis to problem analysis and solution synthesis to problem synthesis) are significantly higher ($p<0.05$) during the ideation activity. Moreover, the probabilities of design operation sequences towards the solution space (problem analysis to solution analysis, problem evaluation to solution evaluation, solution analysis to solution analysis, solution synthesis to solution evaluation and solution evaluation to solution analysis) are significantly higher ($p<0.05$) during the concept review activity. As for the transitions aggregated into ASE, the probabilities of moves from analysis to synthesis, synthesis to synthesis and evaluation to synthesis are significantly higher ($p<0.05$) during the ideation activity, while the probabilities of moves from analysis to analysis, synthesis to analysis and synthesis to evaluation are significantly higher ($p<0.05$) during the concept review activity. Again, as stated in Subsection 4.3.2, one should be cautious when attributing the results of the t-test solely to the nature of ideation and concept review activities.

4.3.3. Moving average analysis of experiment sessions

Since the captured protocols are structured as time series data, it is possible to analyse also the change in proportions of design operations and sequences of design operations over the course of the observed design activity. Such analysis gives insight into foci on particular states and transitions with the progress of the activity. For this purpose, a moving average (windowing) approach (see, e.g. [221], [269], [270]) has been applied on coded protocols, as it provides a qualitative overview of the change in proportions of highly granular data. The moving average calculations create a series of protocol string subsets. The width of the sample window covers a fixed number of protocol segments, which was set here at 15% of the total number of session segments (based on experience, the 15% window offered the best ratio of the number of codes included in a window and the dynamics it has been able to exhibit). Hence, for each protocol segment, the average proportions of design operation codes and their sequences have been calculated by taking into consideration 15% of segments appearing before the analysed protocol segment. The window is moved from the start to the end of the session, one segment at a time.

The moving average analysis of the proportions of ASE design operations within the problem and the solution space during ideation and concept review activity has resulted in graphs shown in Figure 4.9. Hence, similarly to the graphs showing the cumulative proportions of design operations during ideation and concept review (Figure 4.4), the graphs in Figure 4.9 show the change in these proportions over the course of the two activities.

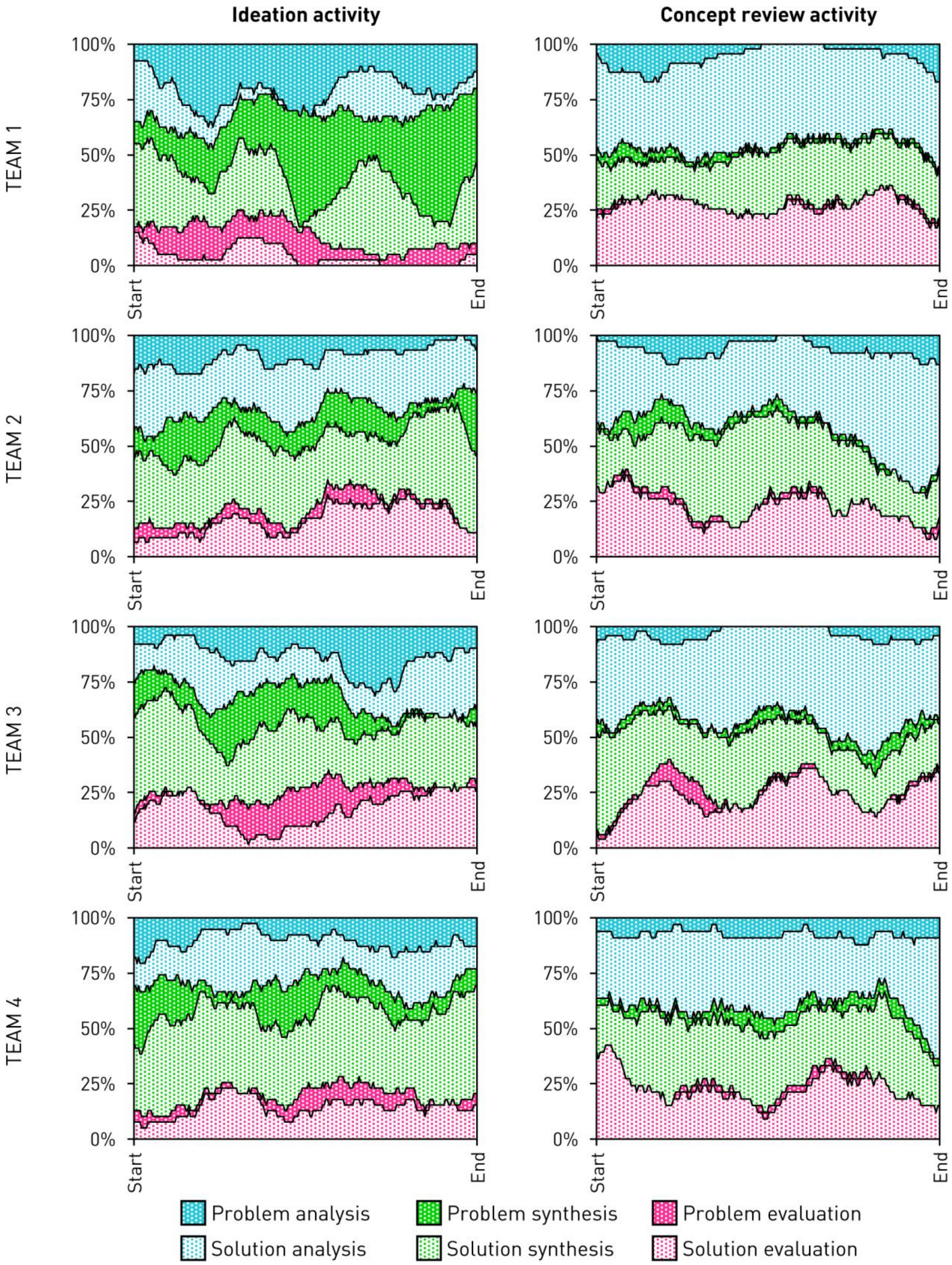

Figure 4.9 Overview of moving average proportions of ASE design operations within problem and solution space during ideation and concept review activities

The change in proportions of ASE design operations can also be represented using the triangular visualisations of ASE proportions (Figure 4.10). Again, analogous to the cumulative proportions of ASE design operations during ideation and concept review shown in Figure 4.5, these visualisations illustrate the change in ASE proportions throughout the two activities. The visualisations are essentially moving average representations of ASE design operation proportions throughout the activity (the resolution of change in proportions depends on the number of segments included within the moving window). Lapp [271] utilised a similar visualisation approach to show how agents explore two dimensions of the solution space.

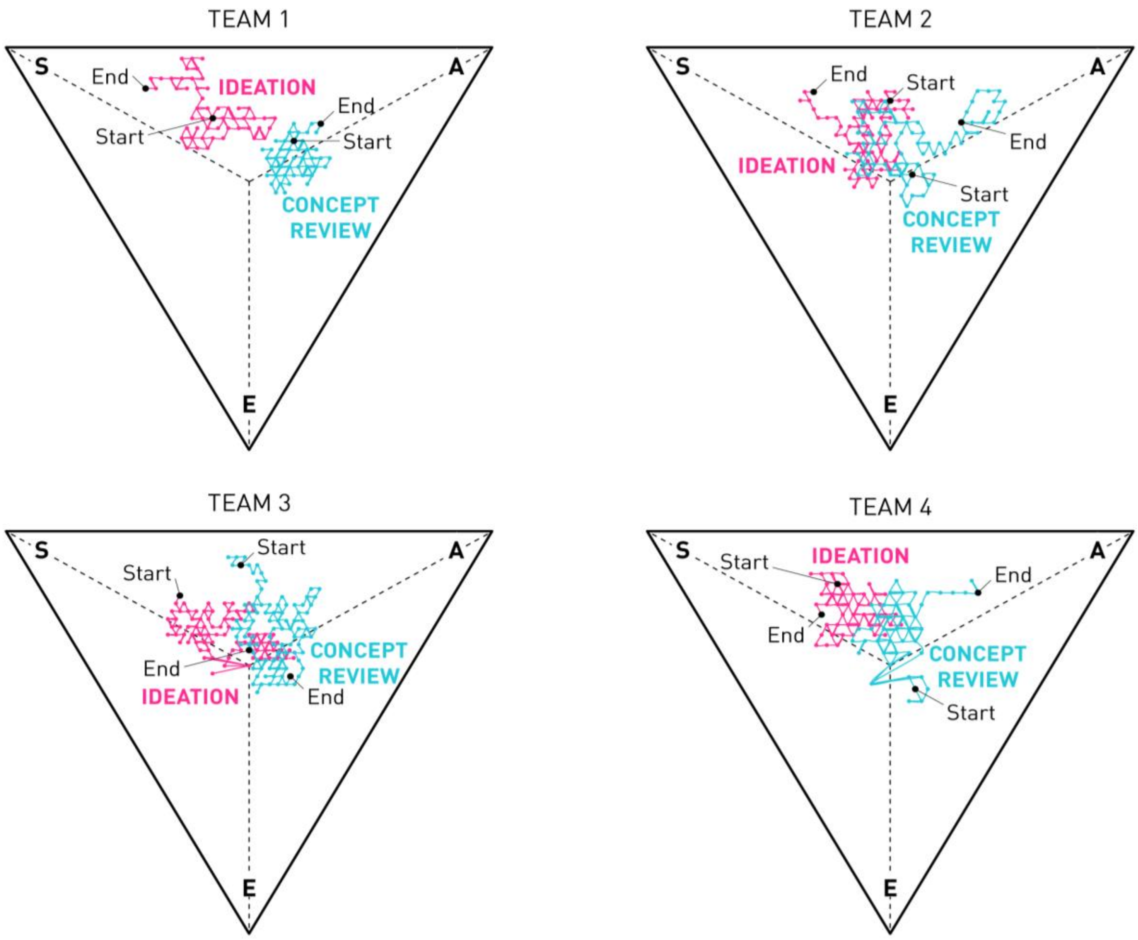

Figure 4.10 Triangular visualisation of moving average proportions of ASE design operations during idetion and concept review activities

Furthermore, moving average analysis can also be performed on proportions of sequences of two design operations. However, due to the relatively large number of moves between two ASE design operations within and in-between the problem and the solution space (36), only the aggregated moving average graphs are here presented. Hence, the changes in proportions of ASE sequences are shown in Figure 4.11, whereas the proportions of the sequences of problem- and solution-related design operations are shown in Figure 4.12.

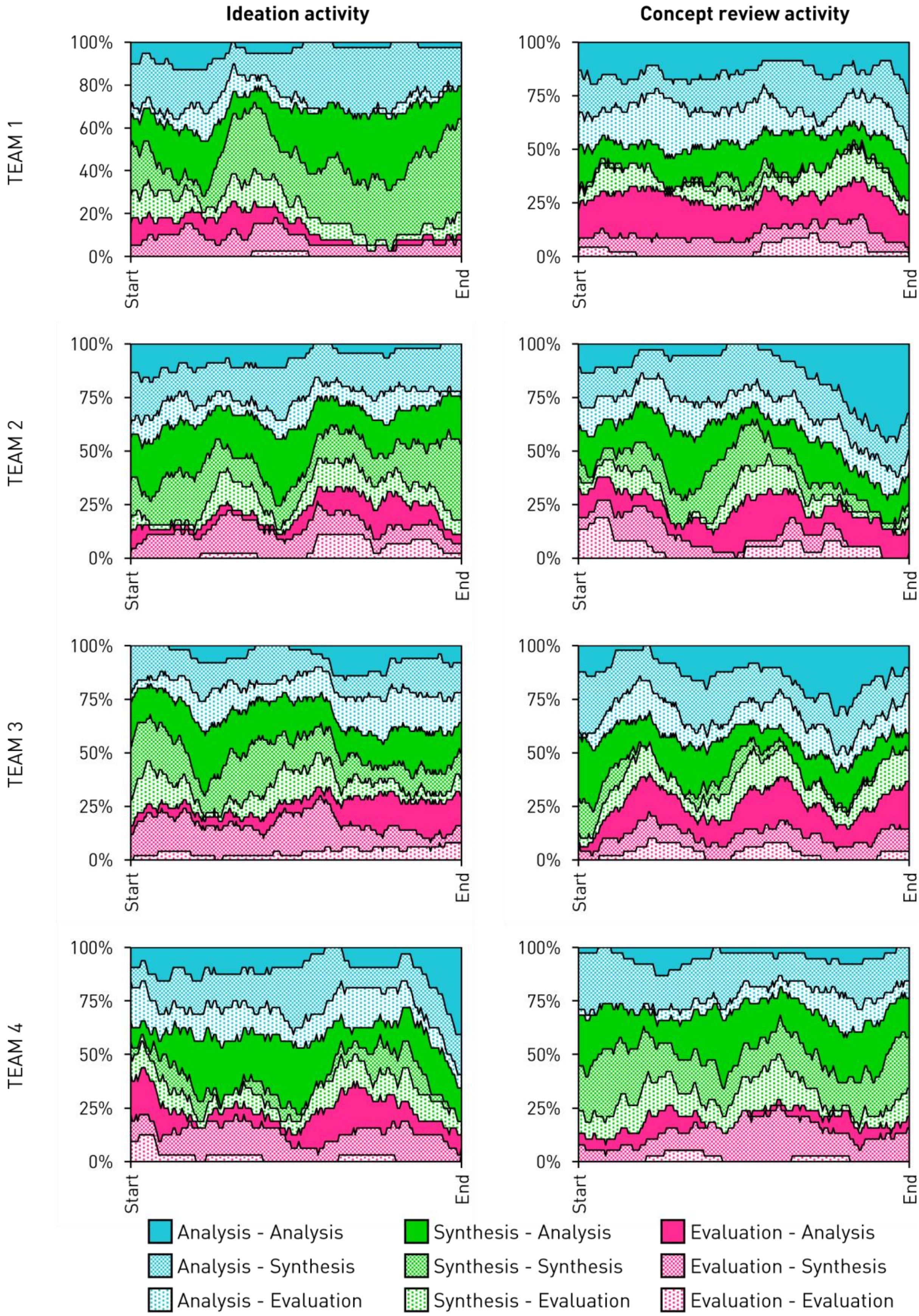

Figure 4.11 Overview of moving average proportions of sequences of ASE during ideation and concept review activities

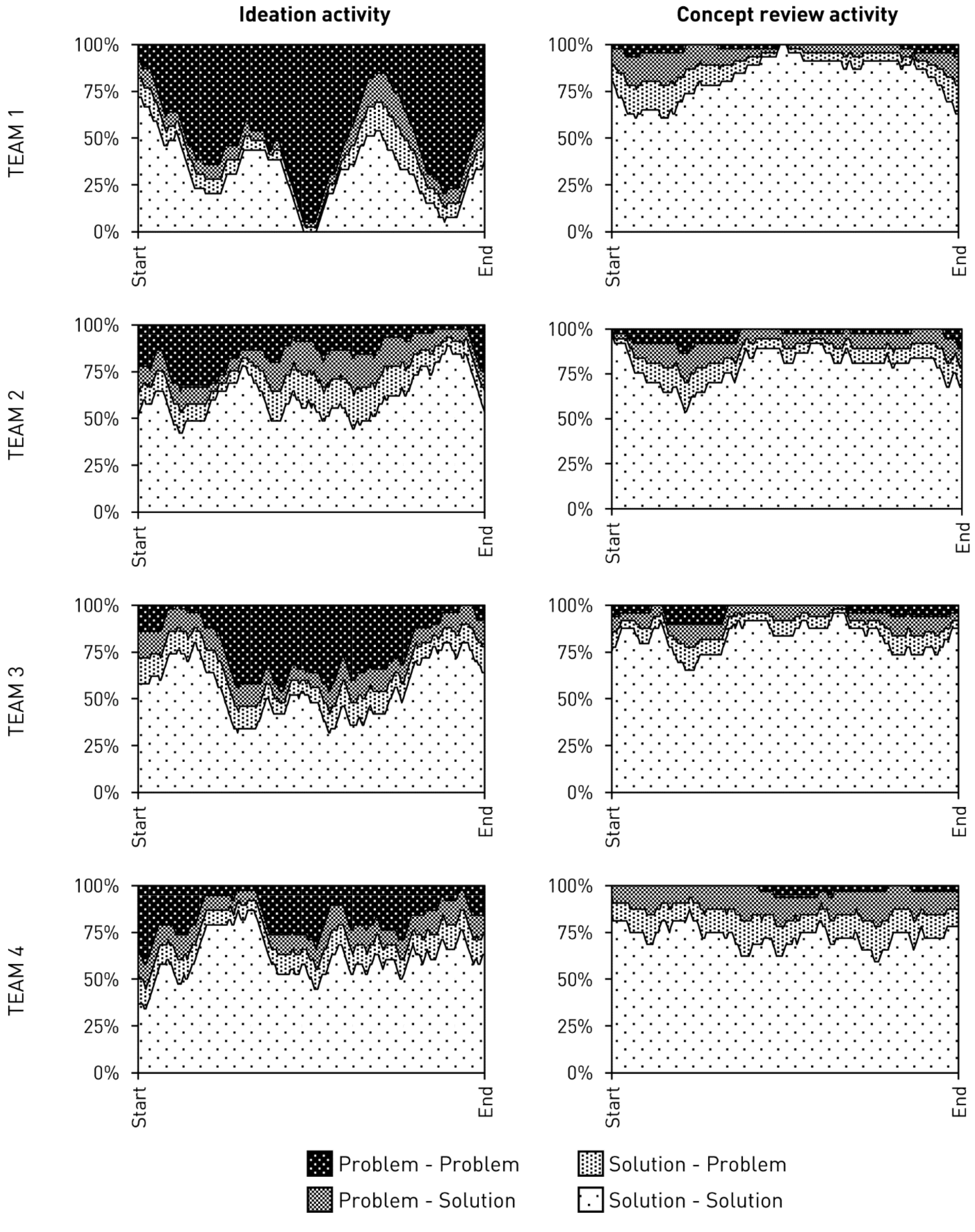

Figure 4.12 Overview of moving average proportions of sequences of problem- and solution-related design operation during ideation and concept review activities

The moving average graphs of proportions of design operations and of sequences of design operations enable qualitative analysis of designing in teams, particularly in terms of the design operations that exhibited high proportions at different periods of the observed design activity.

The graphs reveal there exists an evident dynamic in the proportion change of different types of design operations as well as moves from one type of design operation to the others. The latter applies for the way teams performed ASE as well as how they switched in-between the problem and the solution space. Although they have roughly explored similar parts of the triangular ASE proportion visualisation (Figure 4.10), the teams exhibited largely distinctive proportions of design operations and their sequences at different points in the activity. The overall nature of the teams' processes in regard to these proportions is briefly described hereafter.

The process of Team 1 during ideation activity was the most problem-focused when compared to the other teams. The problem-focus is particularly evident in the form of three periods where problem analysis, synthesis and evaluation exhibit higher proportions (Figure 4.9). These periods are preceded and followed primarily by solution synthesis design operation, with relatively small proportions of solution analysis and evaluation. The process of Team 1 during concept review is significantly different, as shown in Figure 4.9. Problem-related design operations appear in small proportions at the beginning and the end of the session. Moreover, the changes in proportions of design operations are less evident when compared to ideation, as solution analysis and evaluation prevail throughout the whole concept review activity.

In terms of ASE proportions, the ideation and concept review processes of Team 2 partially coincide, as shown in Figure 4.9. Similar proportions of ASE are particularly evident at the beginning of ideation and concept review activities. However, towards the end of ideation, the team progressed towards higher proportions of synthesis, whereas towards the end of concept review, the team progressed towards higher proportions of analysis. During both activities, the problem-related design operations are present mainly at the beginning of the session and decrease towards the end. Nevertheless, similarly to the other teams, the proportion of problem-related design operations is significantly higher throughout ideation when compared to concept review activity.

Team 3 started the ideation activity mainly by focusing on synthesising solutions, followed by evaluating solutions and synthesising problems, before finally analysing the problem and synthesising and analysing solutions. The focus on problem space in the middle of the ideation session is evident in Figure 4.12. A somewhat similar approach can be seen during the concept review, but with notably smaller proportions of problem-related design operations. Concept review thus starts primarily with the synthesis of solutions. Synthesis decreases towards the end of the activity, where solution analysis and evaluation prevail. Unlike during ideation, problem-related design operations are present at the beginning and the end of concept review.

Finally, the ideation process of Team 4 is characterised by problem synthesis and analysis at the beginning and in the middle of the session, and high proportions of solution synthesis throughout the rest of the session. On the other hand, with relatively low proportions of problem analysis and synthesis and negligible proportions of problem evaluation during concept review, the focus is primarily on the development of solution entities. Solution analysis and evaluation thus dominate the beginning and towards the end of concept review, whereas synthesis of solutions is relatively high in the middle of the session.

The protocol analysis results presented in Figures 4.9-4.12 together give a comprehensive and layered overview of the team design activity process, and indicate a possible interplay between the proportions and sequences of design operations. For example, moving average analysis of the particular proportions and sequences of interest can be singled out and plotted onto the same graph, in order to qualitatively investigate the abovementioned interplay. Figure 4.13 shows an example of plotting graphs related to proportions of sequences of solution synthesis design operations during ideation activity of Team 1.

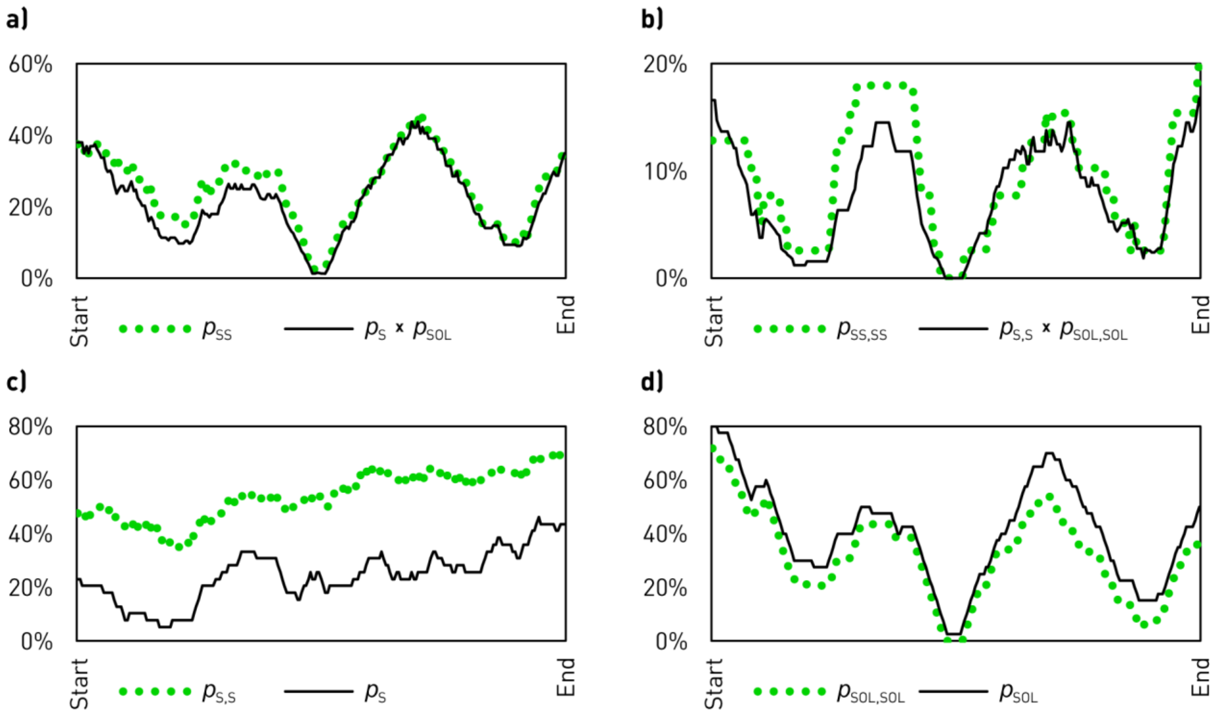

Figure 4.13 Moving average analysis of some possible relationships between variables related to proportions of solution synthesis (p_{SS}) and proportions of moves from solution synthesis to solution synthesis ($p_{SS,SS}$) during ideation activity of Team 1

Figure 4.13a compares the proportion of solution synthesis against the product of proportion of synthesis and proportion of solution-related design operations, thus indicating a possible relationship between these variables. Moreover, Figure 4.13b compares the proportion of moves in-between solution synthesis design operation against the product of moves in-between synthesis and moves in-between solution-related design operations. The proportions of moves in-between synthesis design operations (Figure 4.13c) and in-between solution-related design operations (Figure 4.13d) can in a same manner be related to proportion of synthesis and proportion of solution-related design operations respectively.

Another example, shown in Figure 4.14, concerns the proportion of solution analysis and moves from solution synthesis to solution analysis design operation during the ideation activity of Team 2. Thus, Figure 4.14a compares the proportion of solution analysis against the product of proportion of analysis and proportion of solution-related design operations, whereas Figure 4.14b compares the proportion of moves from solution synthesis to solution analysis design operation against the product of moves from synthesis to analysis and moves in-between solution-related design operations. The proportions of moves from synthesis to analysis design operations (Figure 4.14c) and in-between solution-related design operations (Figure 4.14d) can in a same manner be related to proportion of synthesis and analysis design operations and proportion of solution-related design operations respectively.

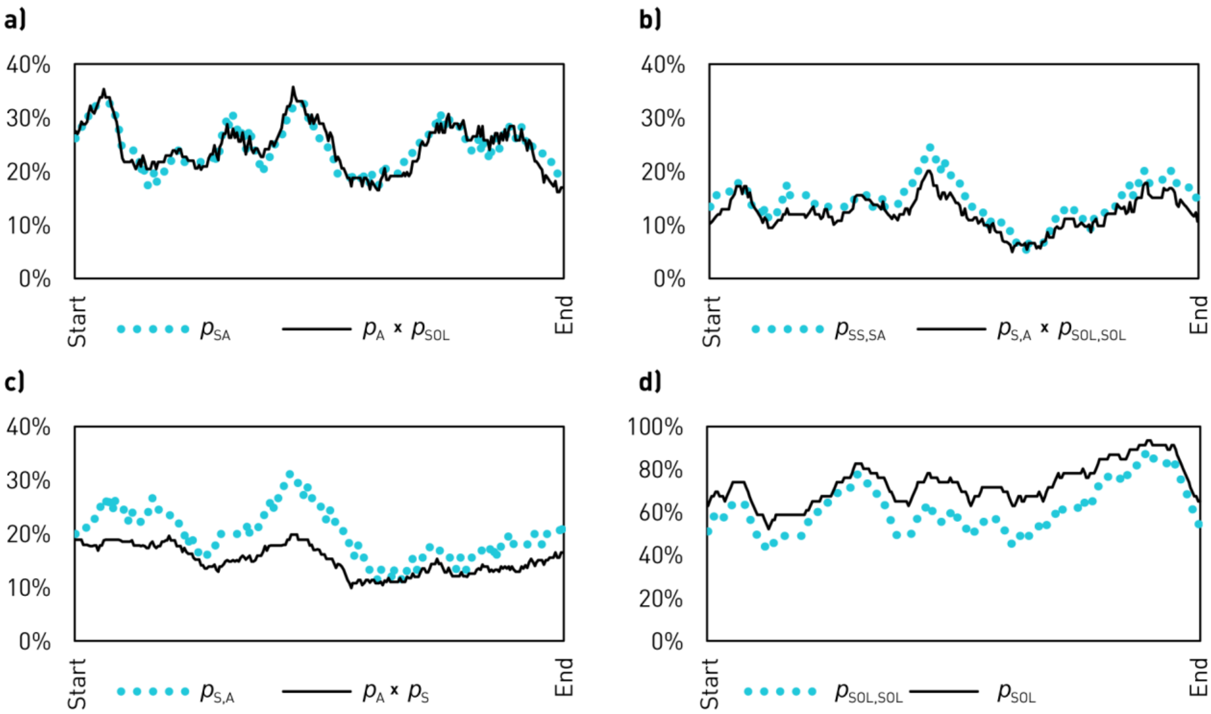

Figure 4.14 Moving average analysis of some possible relationships between variables related to proportions of solution analysis (p_{SA}) and proportions of moves from solution synthesis to solution analysis ($p_{SS,SA}$) during ideation activity of Team 2

Both examples exhibit qualitative pattern similarity (and thus a potential relationship) between the proportions of ASE design operations within the problem and the solution space, the proportions aggregated to ASE and problem- and solution-related design operations, and the proportions of the corresponding sequences of design operations.

The nature of these relationships and the utility of using the relationships to model team conceptual design activity is further explored within the next chapter. The results from the here presented protocol analysis study provide a sufficient dataset for the exploratory analysis and modelling of the hypothesised interplay between proportions and sequences of design operations. The proportions of design operations and their sequences introduced as part of the theoretical model in Chapter 3 are formalised within the mathematical model using the experimental data. The mathematical model can be utilised as a means of simulating proportions and sequences of design operations for different types and arrangements of design tasks throughout the conceptual design stage, as demonstrated in Chapter 6.

5. MATHEMATICAL MODEL

The fifth chapter builds on the results of the protocol analysis study, primarily by means of statistical and stochastic modelling of relationships identified within the obtained protocol data. The relationships between proportions of design operations and proportions of their sequences have been formalised using regression analysis. The resulting regression equations have then been synthesised in the form of a mathematical model of state transitions during team conceptual design activity. Finally, the mathematical model has been tested by replicating the results of the protocol analysis study.

The previous chapter presents the results of utilising the theoretical framework as a means of gathering, structuring and analysing data related to design information processing in team conceptual design activity. This chapter furthermore investigates the potential relationships within the interpreted data (some of which are indicated at the end of Subsection 4.3.3), and utilises the protocol analysis results for the modelling of proportions and probabilities of sequences of design operations throughout the conceptual design stage. In the context of this dissertation, the ability to model and simulate conceptual design information processing is essential for addressing research questions RQ4 and RQ5, that is how the identified patterns of ASE design operations are likely to change with the progress of the conceptual design stage and what are the prevalent patterns of ASE design operations in different types of engineering design projects (e.g. innovative and adaptive design).

The regression analysis has been used to quantify the relationships [272] in-between the state-transition variables introduced within Chapter 3. Regression analysis has been assessed as the most appropriate means of investigating and modelling a wide variety of relationships between large sets of variables. Simple regression involves only two variables – a predictor (independent) variable and a response (dependent) variable. Multiple regression is an obvious generalisation of simple linear regression, as it allows multiple predictor variables instead of one predictor variable [272]. Generally, when applying linear regression, the observed data is used to fit a model of the relationship between a scalar dependent variable and one or more explanatory (independent) variables [273]. For the development of here-presented mathematical model, linear and polynomial regression analysis were performed to investigate the relationships between proportions and sequences of design operations. The linear regression approach is simple to apply but assumes that the variables in the regression are linear and that the effect of independent variables is constant throughout the entire range of the response variable [274]. Polynomial regression is (from here on) considered a special case of multiple linear regression.

Given the theoretical framework described within Chapter 3, a total of three fundamental independent variables have been identified: two variables which define the vector within the ASE proportion triangle (distance from the triangle centre r and angle δ), which corresponds to the proportions of analysis, synthesis and evaluation (Equations 3.5-3.7), and one variable which defines the ratio of proportions of problem- and solution-related design operations. These three independent variables thus represent the input parameters needed for calculating (predicting) the dependent variables, that is the proportions and probabilities of sequences of ASE design operation within and in-between the problem and the solution space (e.g. using computational simulation tools). For the sake of simplicity, the vector variables and the problem/solution ratio have not been directly used. Instead, the regression has been performed using the proportions of analysis, synthesis and evaluation ($p_{\mathrm{A}} + p_{\mathrm{S}} + p_{\mathrm{E}} = 1$), and the proportions of problem- and solution-related design operations ($p_{\mathrm{PRO}} + p_{\mathrm{SOL}} = 1$).

Linear regression modelling was conducted using the R software [272], [275]. Since the effects of intercepts are not significant, they have been excluded from the linear regression analysis. In this way, only one coefficient is sufficient to describe a particular relationship. Moreover, the regression models include only interactions terms or squared terms (without including the main effects). There are two reasons for this. First, the main effects have in general not been found significant. Second, the modelling purpose is solely to predict proportions of design operations and their sequences, rather than statistical inference about each of the effects. The normality of the error distribution in the regression models was tested using the Shapiro-Wilk test [272]. These results are also reported hereafter. Other linear regression diagnostics have been performed as part of the modelling process by plotting diagnostic plots (observed versus predicted values, residuals versus predicted values).

The results of linear regression modelling are reported in two parts. In Section 5.1, the proportions of design operations p_{PA}, p_{PS}, p_{PE}, p_{SA}, p_{SS} and p_{SE} are formulated as functions of ASE proportions and the proportions of the problem- and solution-related design operations. In Section 5.2, the proportions of sequences of two design operations are formulated as functions of design operation proportions (both aggregated – e.g. $p_{\mathrm{A,A}}$, $p_{\mathrm{A,S}}$, $p_{\mathrm{PRO,PRO}}$, etc. – and unaggregated – e.g. $p_{\mathrm{PA,PA}}$, $p_{\mathrm{PA,PS}}$, etc.). Finally, in Section 5.3, all formulated regression equations are integrated as part of a single mathematical model, and the model is used to generate data related to design operation proportions and sequences, with input variables being the data from the protocol analysis study. A qualitative comparison of the observed and simulated data is then performed to initially validate the predictive ability of the mathematical model.

5.1. Modelling proportions of design operations

Several iterations of linear regression modelling have been conducted on the design operation proportions data gathered from the protocol analysis study (Chapter 4). The best fit has been reached for the following hypothesised relationship: *The proportion of either one of ASE design operations within the problem or the solution space is proportional to the product of the corresponding proportions of ASE and problem/solution-related design operations.*

Symbolically, the formulated relationship can be written as shown in Equation 5.1.

$$p_{xy} = k_{xy} \cdot p_x \cdot p_y\,, \qquad x = \{PRO;SOL\}, \quad y = \{A;S;E\} \qquad \text{(Equation 5.1)}$$

The initial number of data points for linear regression was relatively small – one point per observed experiment session (8 data points in total), which corresponds to the average proportions of design operations during the whole activity (reported throughout the Subsection 4.3.1). In order to increase the number of data points, the protocol strings, which consist of 221-341 design operations codes, have been split into two and three equal subsets of protocol strings. Such splitting resulted in 16 and 24 data points respectively. The rationale for splitting the protocol strings lies in the assumption that the hypothesised relationships should be consistent not only on the activity level but also for different fragments of the activity. The fitting results of the regression analysis using 8, 16 and 24 points (based on one, two and three fragments of the experiment sessions) are shown in Figure 5.1.

The results confirm the assumption that the relationship between proportions is consistent no matter which fragment of activity is observed – namely, the differences between the three cases of linear regression range from 0.1% to 5.2%. Furthermore, the higher the number of instances of a particular design operation (n_i) in a protocol string, the more insignificant difference exists between the three cases of linear regression. For example, solution analysis, synthesis and evaluation design operations, which were the most frequent instances on average, exhibit only 0.1%, 0.2% and 0.2% difference respectively, whereas problem evaluation as the least frequent instance manifests 5.2% difference. Hence, increasing the number of data points by splitting the initial protocol strings into smaller fragments can be performed as long as a sufficient number of instances of each design operations is present within the protocol string fragments.

For this reason, the splitting of protocol strings into more than three fragments has not been performed. The relationships described hereafter result from analysis using 24 data points.

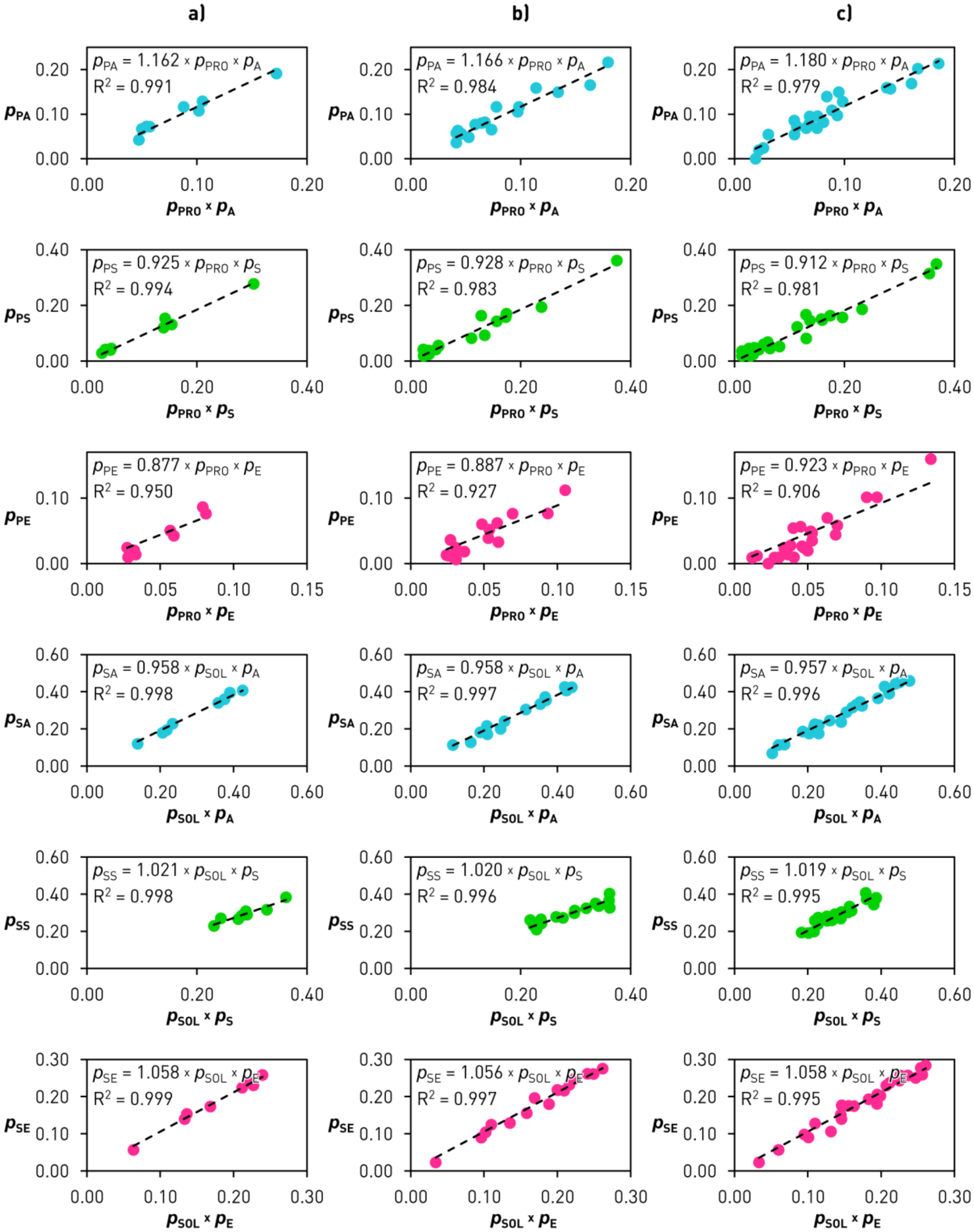

Figure 5.1 Relations between unaggregated design operations as dependent variables and design operations aggregated into ASE and problem/solution as independent variables: a) total activities; b) activities split into two parts; c) activities split into three parts

Proportion of problem analysis – A multiple linear regression was calculated to predict the proportion of problem analysis based on the interaction of proportions of analysis and problem-related design operations. A significant regression equation (Equation 5.2) was found ($F(1,23)=1076$, $p<0.000$) with an $R^2=0.979$. The interaction significantly predicted the proportion of problem analysis ($\beta=0.989$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.928$, $p=0.088$).

$$p_{\mathrm{PA}} = 1.180 \cdot p_{\mathrm{A}} \cdot p_{\mathrm{PRO}} \qquad \text{(Equation 5.2)}$$

Proportion of problem synthesis – A multiple linear regression was calculated to predict the proportion of problem synthesis based on the interaction of proportions of synthesis and problem-related design operations. A significant regression equation (Equation 5.3) was found ($F(1,23)=1195$, $p<0.000$) with an $R^2=0.981$. The interaction significantly predicted the proportion of problem synthesis ($\beta=0.991$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.974$, $p=0.772$).

$$p_{\mathrm{PS}} = 0.912 \cdot p_{\mathrm{S}} \cdot p_{\mathrm{PRO}} \qquad \text{(Equation 5.3)}$$

Proportion of problem evaluation – A multiple linear regression was calculated to predict the proportion of problem evaluation based on the interaction of proportions of evaluation and problem-related design operations. A significant regression equation (Equation 5.4) was found ($F(1,23)=222.8$, $p<0.000$) with an $R^2=0.906$. The interaction significantly predicted the proportion of problem evaluation ($\beta=0.952$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.938$, $p=0.150$).

$$p_{\mathrm{PE}} = 0.923 \cdot p_{\mathrm{E}} \cdot p_{\mathrm{PRO}} \qquad \text{(Equation 5.4)}$$

Proportion of solution analysis – A multiple linear regression was calculated to predict the proportion of solution analysis based on the interaction of proportions of analysis and solution-related design operations. A significant regression equation (Equation 5.5) was found ($F(1,23)=5388$, $p<0.000$) with an $R^2=0.996$. The interaction significantly predicted the proportion of solution analysis ($\beta=0.998$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.977$, $p=0.845$).

$$p_{\mathrm{SA}} = 0.957 \cdot p_{\mathrm{A}} \cdot p_{\mathrm{SOL}} \qquad \text{(Equation 5.5)}$$

Proportion of solution synthesis – A multiple linear regression was calculated to predict the proportion of solution synthesis based on the interaction of proportions of synthesis and solution-related design operations. A significant regression equation (Equation 5.6) was found ($F(1,23)=4217$, $p<0.000$) with an $R^2=0.995$. The interaction significantly predicted the proportion of solution synthesis (β=0.997, p<0.000). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 (W=0.957, p=0.372).

$$p_{\mathrm{SS}} = 1.019 \cdot p_{\mathrm{S}} \cdot p_{\mathrm{SOL}} \qquad \text{(Equation 5.6)}$$

Proportion of solution evaluation – A multiple linear regression was calculated to predict the proportion of solution evaluation based on the interaction of proportions of evaluation and solution-related design operations. A significant regression equation (Equation 5.7) was found (F(1,23)=4854, p<0.000) with an R^2=0.995. The interaction significantly predicted the proportion of solution synthesis (β=0.998, p<0.000). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 (W=0.973, p=0.743).

$$p_{\mathrm{SE}} = 1.058 \cdot p_{\mathrm{E}} \cdot p_{\mathrm{SOL}} \qquad \text{(Equation 5.7)}$$

The above-listed equations enable modelling of proportions of six ASE design operations in problem and solution space based on the three independent variables. The response can be used to perform moving average analysis of design operations proportions as shown in Figure 4.9 and gain qualitative insights about team conceptual design activities that can be characterised using the three independent variables. The ability of the formulated linear regression models to reflect design operation proportions captured in the protocol analysis study is investigated in Section 5.3.

5.2. Modelling sequences of design operations

The modelling of proportions of design operation sequences has been conducted in a similar manner as modelling proportions of design operations. The relationship hypothesis investigated through several iterations of simple and multiple linear regression modelling was that the proportions of moves between two design operations are proportional to the product of proportions of these two design operations.

5.2.1. Sequences of ASE design operations

The modelling was first conducted for the proportions of moves between analysis, synthesis and evaluation (design operations aggregated into ASE). The following relationship has been hypothesised based on the regression modelling best fit: *The proportion of moves between two ASE design operations is proportional to the product of the corresponding proportions of ASE design operations.* Symbolically, this relationship can be written as shown in Equation 5.8.

$$p_{\mathrm{x,y}} = k_{\mathrm{x,y}} \cdot p_{\mathrm{x}} \cdot p_{\mathrm{y}}\,, \qquad \mathrm{x,y} = \{\mathrm{A;S;E}\} \qquad \text{(Equation 5.8)}$$

As shown in Figure 5.2, linear regression has again been performed for three cases: the complete protocol strings (8 data points), protocol strings split into two fragments (16 data points), and protocol strings split into three fragments (24 data points). The results confirm the assumption that the relationship between proportions is consistent no matter which fragment of activity is observed since the differences in-between the three cases of linear regression range from 0.7% to 4.2%. Again, the highest difference was found for the sequence with the lowest number of instances within the fragments (evaluation to evaluation).

Proportion of analysis to analysis sequences – A simple linear regression was calculated to predict the proportion of moves from analysis to analysis based on the squared proportion of analysis design operation. A significant regression equation (Equation 5.9) was found ($F(1,23)=287.8$, $p<0.000$) with an $R^2=0.926$. The squared proportion significantly predicted the proportion of analysis to analysis sequences ($\beta=0.962$, $p<0.000$). However, the Shapiro-Wilk test rejected the normality assumption at the significance level of 0.05 ($W=0.876$, $p=0.007$). The issue of non-normal error distribution is addressed in Section 5.3.

$$p_{\mathrm{A,A}} = 0.703 \cdot p_{\mathrm{A}}^2 \qquad \text{(Equation 5.9)}$$

Proportion of analysis to synthesis sequences – A multiple linear regression was calculated to predict the proportion of moves from analysis to synthesis based on the interaction of proportions of analysis and proportion of synthesis design operations. A significant regression equation (Equation 5.10) was found ($F(1,23)=1452$, $p<0.000$) with an $R^2=0.984$. The interaction significantly predicted the proportion of analysis to synthesis sequences ($\beta=0.992$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.943$, $p=0.194$).

$$p_{\mathrm{A,S}} = 1.253 \cdot p_{\mathrm{A}} \cdot p_{\mathrm{S}} \qquad \text{(Equation 5.10)}$$

Proportion of analysis to evaluation sequences – A multiple linear regression was calculated to predict the proportion of moves from analysis to evaluation based on the interaction of proportions of analysis and proportion of evaluation design operations. A significant regression equation (Equation 5.11) was found ($F(1,23)=691.3$, $p<0.000$) with an $R^2=0.968$. The interaction significantly predicted the proportion of analysis to evaluation sequences ($\beta=0.984$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.981$, $p=0.917$).

$$p_{\mathrm{A,E}} = 1.194 \cdot p_{\mathrm{A}} \cdot p_{\mathrm{E}} \qquad \text{(Equation 5.11)}$$

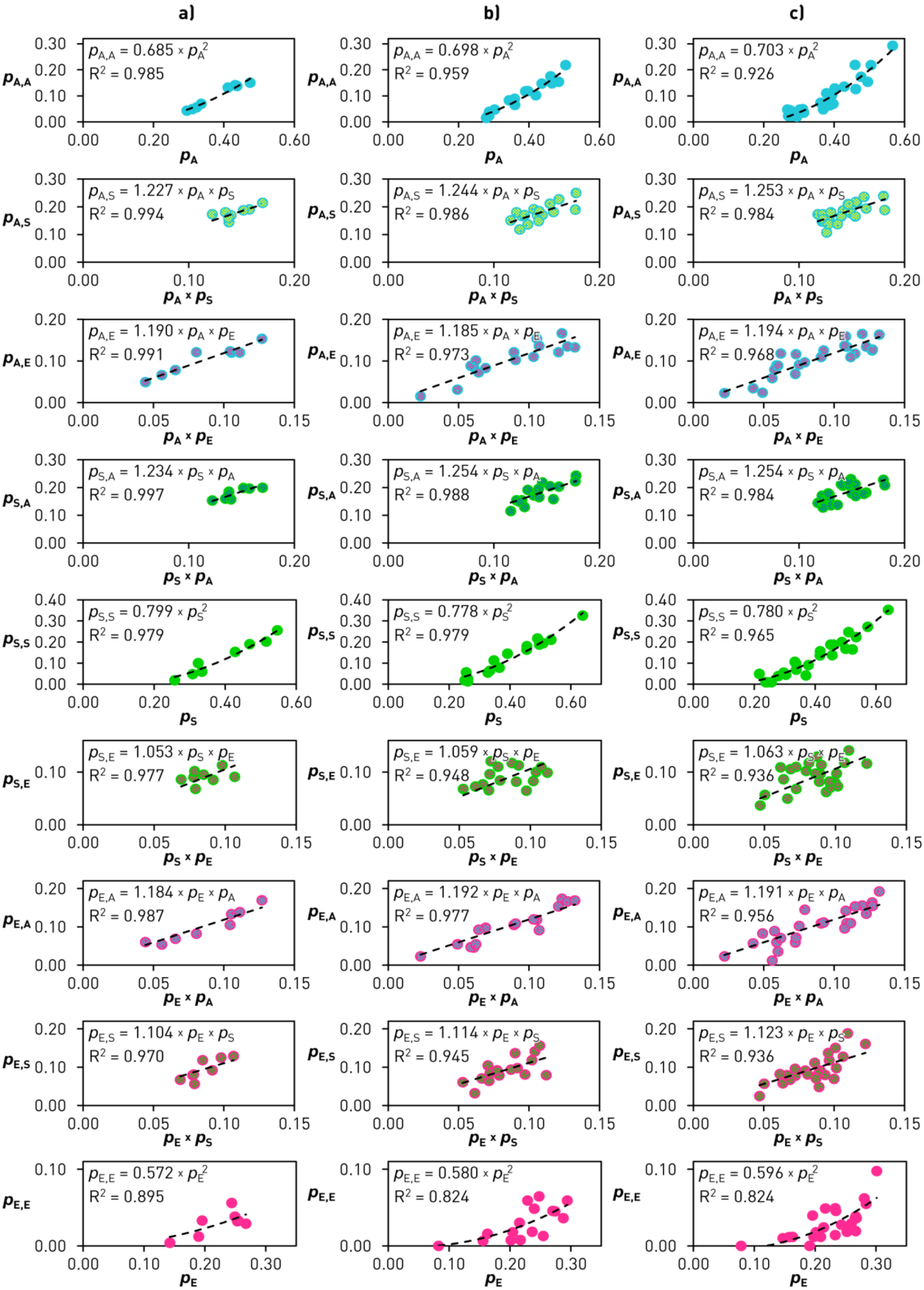

Figure 5.2 Relations between proportions of sequences of two design operations as dependent variables and proportions of design operations as independent variables: a) total activities; b) activities split into two parts; c) activities split into three parts

Proportion of synthesis to analysis sequences – A multiple linear regression was calculated to predict the proportion of moves from synthesis to analysis based on the interaction of proportions of synthesis and proportion of analysis design operations. A significant regression equation (Equation 5.12) was found (F(1,23)=1384, p<0.000) with an R^2=0.984. The interaction significantly predicted the proportion of synthesis to analysis sequences (β=0.992, p<0.000). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 (W=0.938, p=0.145).

$$p_{\mathrm{S,A}} = 1.254 \cdot p_{\mathrm{S}} \cdot p_{\mathrm{A}} \qquad \text{(Equation 5.12)}$$

Proportion of synthesis to synthesis sequences – A simple linear regression was calculated to predict the proportion of moves from synthesis to synthesis based on the squared proportion of synthesis design operation. A significant regression equation (Equation 5.13) was found (F(1,23)=630.3, p<0.000) with an R^2=0.965. The squared proportion significantly predicted the proportion of synthesis to synthesis sequences (β=0.982, p<0.000). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 (W=0.965, p=0.562).

$$p_{\mathrm{S,S}} = 0.780 \cdot p_{\mathrm{S}}^2 \qquad \text{(Equation 5.13)}$$

Proportion of synthesis to evaluation sequences – A multiple linear regression was calculated to predict the proportion of moves from synthesis to evaluation based on the interaction of proportions of synthesis and proportion of evaluation design operations. A significant regression equation (Equation 5.14) was found (F(1,23)=335.1, p<0.000) with an R^2=0.936. The interaction significantly predicted the proportion of synthesis to evaluation sequences (β=0.967, p<0.000). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 (W=0.953, p=0.318).

$$p_{\mathrm{S,E}} = 1.063 \cdot p_{\mathrm{S}} \cdot p_{\mathrm{E}} \qquad \text{(Equation 5.14)}$$

Proportion of evaluation to analysis sequences – A multiple linear regression was calculated to predict the proportion of moves from evaluation to analysis based on the interaction of proportions of evaluation and proportion of analysis design operations. A significant regression equation (Equation 5.15) was found (F(1,23)=495, p<0.000) with an R^2=0.956. The interaction significantly predicted the proportion of evaluation to analysis sequences (β=0.978, p<0.000). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 (W=0.991, p=0.998).

$$p_{\mathrm{E,A}} = 1.191 \cdot p_{\mathrm{E}} \cdot p_{\mathrm{A}} \qquad \text{(Equation 5.15)}$$

Proportion of evaluation to synthesis sequences – A multiple linear regression was calculated to predict the proportion of moves from evaluation to synthesis based on the interaction of proportions of evaluation and proportion of synthesis design operations. A significant regression equation (Equation 5.16) was found ($F(1,23)=333.6$, $p<0.000$) with an $R^2=0.936$. The interaction significantly predicted the proportion of evaluation to analysis sequences ($\beta=0.967$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.983$, $p=0.943$).

$$p_{\mathrm{E,S}} = 1.123 \cdot p_{\mathrm{E}} \cdot p_{\mathrm{S}} \qquad \text{(Equation 5.16)}$$

Proportion of evaluation to evaluation sequences – A simple linear regression was calculated to predict the proportion of moves from evaluation to evaluation based on the squared proportion of evaluation design operation. A significant regression equation (Equation 5.17) was found ($F(1,23)=107.8$, $p<0.000$) with an $R^2=0.824$. The squared proportion significantly predicted the proportion of evaluation to evaluation sequences ($\beta=0.908$, $p<0.000$). However, the Shapiro-Wilk test rejected the normality assumption at the significance level of 0.05 ($W=0.910$, $p=0.034$). Again, the issue of non-normal error distribution is addressed in Section 5.3.

$$p_{\mathrm{E,E}} = 0.596 \cdot p_{\mathrm{E}}^2 \qquad \text{(Equation 5.17)}$$

The aforementioned equations enable modelling of proportions of nine possible sequences of two ASE design operations based on the three independent variables. The response provided by the equations can be used to perform moving average analysis of ASE design operations sequences as shown in Figure 4.11 and gain qualitative insights into patterns of performing ASE design operations during team conceptual design activities that can be characterised using the three independent variables. Nevertheless, the normality of residuals assumption has been violated for two regression models; hence the corresponding equations have not been directly implemented in further developments. More information on the implementation and the ability of the formulated linear regression models to reflect ASE design operation sequences captured in the protocol analysis study is investigated in Section 5.3.

5.2.2. Sequences of problem- and solution-related design operations

The subsequent regression analysis considered sequences of two design operations aggregated into problem- and solution-related design operations. Symbolically, this relationship can be written as shown in Equations 5.18 and 5.19. In the case of sequences of problem- and solution-related design operations, linear regression has been performed for three cases (Figure 5.3): the complete protocol strings (8 data points), protocol strings split into two fragments (16 data points), and protocol strings split into three fragments (24 data points).

$$p_{x,x} = k_{x,x} \cdot p_x^2 \ , \qquad x = \{PRO;SOL\} \qquad \text{(Equation 5.18)}$$

$$p_{x,y} = p_y - p_{y,y} = k1_{x,y} \cdot p_y^2 + k2_{x,y} \cdot p_y \ , \ x = \{PRO;SOL\}, \ y = \{PRO;SOL\} \qquad \text{(Equation 5.19)}$$

The results again confirm the assumption of consistent relationships, with differences in-between the three cases of linear regression ranging from 0.8% to 3.5%. Since two coefficients have been used to model moves from problem to solution space and from solution to problem space, these proportions can be calculated simply by subtracting proportion of problem-problem moves from the proportion of problem-related design operations, and subtracting proportion of solution-solution moves from the proportion of solution-related design operations respectively (as shown in the first part of Equation 5.19). The relationships described hereafter concern the linear regression analysis using 24 data points.

Proportion of problem space to problem space sequences – A simple linear regression was calculated to predict the proportion of moves from problem space to problem space based on the squared proportion of problem-related design operation. A significant regression equation (Equation 5.20) was found ($F(1,23)=980.5$, $p<0.000$) with an $R^2=0.977$. The squared proportion significantly predicted the proportion of problem- to problem-related design operation sequences ($\beta=0.988$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.957$, $p=0.389$).

$$p_{PRO,PRO} = 1.581 \cdot p_{PRO}^2 \qquad \text{(Equation 5.20)}$$

Proportion of problem space to solution space sequences – A multiple linear regression was calculated to predict the proportion of moves from problem space to solution space based on the product of the proportion of problem-related and the proportion of solution-related design operations. A significant regression equation (Equation 5.21) was found ($F(2,22)=234.1$, $p<0.000$) with an $R^2=0.955$. Both the squared proportion ($\beta=-2.143$, $p<0.000$) and the proportion ($\beta=3.044$, $p<0.000$) significantly predicted the proportion of problem- to solution-related design operation sequences. Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.951$, $p=0.288$).

$$p_{PRO,SOL} = -0.337 \cdot p_{SOL}^2 + 0.394 \cdot p_{SOL} \qquad \text{(Equation 5.21)}$$

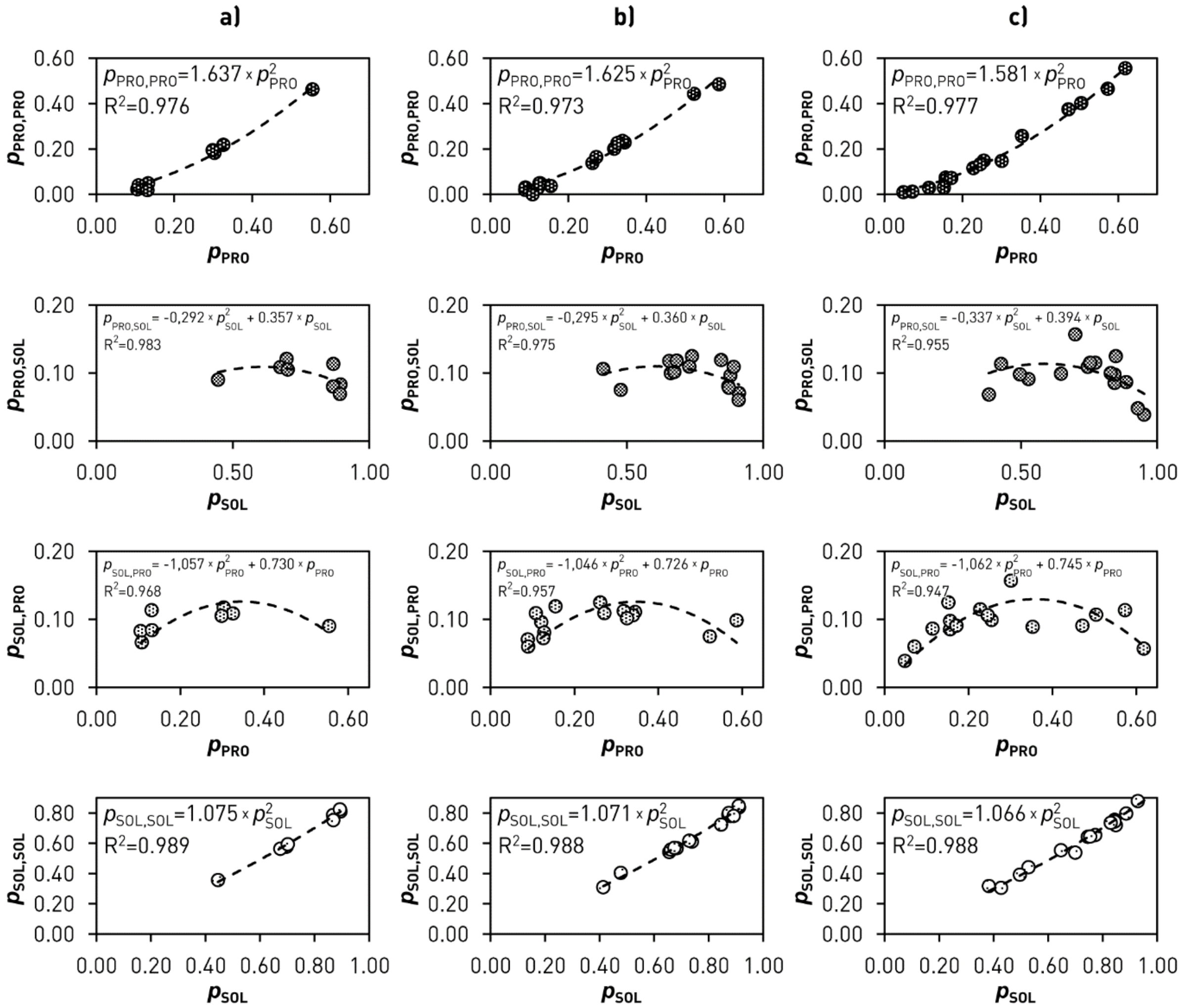

Figure 5.3 Relations between proportions sequences of problem and solution-related design operations as dependent variables and proportions of problem- and solution-related design operations as independent variables:

a) total activities; b) activities split into two parts; c) activities split into three parts

Proportion of solution space to problem space sequences – A multiple linear regression was calculated to predict the proportion of moves from solution space to problem space based on the product of the proportion of solution-related and the proportion of problem-related design operations. A significant regression equation (Equation 5.22) was found ($F(2,22)=195.5$, $p<0.000$) with an $R^2=0.947$. Both the squared proportion ($\beta=-1.432$, $p<0.000$) and the proportion ($\beta=2.186$, $p<0.000$) significantly predicted the proportion of problem- to solution-related design operation sequences. Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.967$, $p=0.593$).

$$p_{\mathrm{SOL,PRO}} = -1.062 \cdot p_{\mathrm{PRO}}^2 + 0.745 \cdot p_{\mathrm{PRO}} \qquad \text{(Equation 5.22)}$$

Proportion of solution space to solution space sequences – A simple linear regression was calculated to predict the proportion of moves from solution space to solution space based on the squared proportion of solution-related design operation. A significant regression equation (Equation 5.23) was found ($F(1,23)=1949$, $p<0.000$) with an $R^2=0.988$. The squared proportion significantly predicted the proportion of solution- to solution-related design operation sequences ($\beta=0.994$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.922$, $p=0.064$).

$$p_{\mathrm{SOL,SOL}} = 1.066 \cdot p_{\mathrm{SOL}}^2 \qquad \text{(Equation 5.23)}$$

The above equations describe the proportions of four possible sequences of the problem- and solution-related design operations based on the three independent variables. These equations enable moving average analysis of problem/solution sequences as shown in Figure 4.12 and gain qualitative insights into patterns of switching in-between the problem and the solution space during team conceptual design activities that can be characterised using the three independent variables. As it is the case with sequences of ASE, the ability of the formulated linear regression models to reflect problem- and solution-related design operation sequences captured in the protocol analysis study is investigated in Section 5.3.

5.2.3. Sequences of ASE within and in-between problem and solution space

Finally, regression analysis has also been conducted to model sequences of ASE design operations within and in-between the problem and the solution space. In this step, the previously reported regression models of sequences of design operations aggregated into ASE and problem/solution-related are utilised as independent variables. At the core, this procedure is identical to formulating the relationships of proportions of ASE design operations in the problem and the solution space and the proportions of ASE and problem/solution-related design operations.

Hence, a hypothesised relationship is formulated as follows: *proportions of moves between two ASE design operations within and in-between the problem and the solution space are proportional to the product of the corresponding proportions of moves between ASE and the proportions of moves between the problem/solution-related design operations*. Symbolically, this relationship can be written as shown in Equation 5.24.

$$p_{\mathrm{xw,yz}} = k_{\mathrm{xw,yz}} \cdot p_{\mathrm{xw}} \cdot p_{\mathrm{yz}}\,, \qquad \mathrm{x,y} = \{\mathrm{PRO;SOL}\}, \quad \mathrm{w,z} = \{\mathrm{A;S;E}\} \qquad \text{(Equation 5.24)}$$

Due to a relatively large number of possible sequences, the results of the linear regression modelling have not been plotted. Instead, the equation coefficients, F-statistics, p-values and R^2 are reported in Tables 5.1 and 5.2. Unlike the case with previously reported models, linear regression modelling has been conducted using only 8 data points, that is without splitting the initial protocol strings. The reason for this is that due to the smaller number of sequences, the shorter fragments of protocol strings do not contain all possible instances of sequences of two design operations, making the results unreliable.

The effect of the lower number of particular instances of design operations sequences (e.g. instances where teams moved from solution space to problem evaluation) is reflected in lower R^2 values of the corresponding equations in Tables 5.1 and 5.2. For example, no significant equations were found for the problem synthesis - solution evaluation, solution synthesis - problem evaluation and solution evaluation - problem evaluation moves (p-value > 0.05).

Table 5.1 Linear regression models of sequences of two ASE design operations within and in-between problem and solution space

Equation (including coefficient)	F-statistic	p-value	R^2
$p_{PA,PA} = 1.239 \cdot p_{PRO,PRO} \cdot p_{A,A}$	F(1,7) = 55.39	p<0.001**	0.888
$p_{PA,PS} = 0.978 \cdot p_{PRO,PRO} \cdot p_{A,S}$	F(1,7) = 403.9	p<0.000**	0.983
$p_{PA,PE} = 1.374 \cdot p_{PRO,PRO} \cdot p_{A,E}$	F(1,7) = 467.6	p<0.000**	0.985
$p_{PA,SA} = 1.478 \cdot p_{PRO,SOL} \cdot p_{A,A}$	F(1,7) = 25.33	p<0.005**	0.784
$p_{PA,SS} = 1.834 \cdot p_{PRO,SOL} \cdot p_{A,S}$	F(1,7) = 60.03	p<0.001**	0.897
$p_{PA,SE} = 0.597 \cdot p_{PRO,SOL} \cdot p_{A,E}$	F(1,7) = 8.014	p<0.050*	0.534
$p_{PS,PA} = 1.023 \cdot p_{PRO,PRO} \cdot p_{S,A}$	F(1,7) = 179.6	p<0.000**	0.963
$p_{PS,PS} = 0.790 \cdot p_{PRO,PRO} \cdot p_{S,S}$	F(1,7) = 144.8	p<0.000**	0.954
$p_{PS,PE} = 1.262 \cdot p_{PRO,PRO} \cdot p_{S,E}$	F(1,7) = 229.7	p<0.000**	0.970
$p_{PS,SA} = 0.213 \cdot p_{PRO,SOL} \cdot p_{S,A}$	F(1,7) = 10.98	p<0.050*	0.611
$p_{PS,SS} = 1.613 \cdot p_{PRO,SOL} \cdot p_{S,S}$	F(1,7) = 53.78	p<0.001**	0.885
$p_{PS,SE} = 0.499 \cdot p_{PRO,SOL} \cdot p_{S,E}$	F(1,7) = 4.583	p>0.050	0.396
$p_{PE,PA} = 1.228 \cdot p_{PRO,PRO} \cdot p_{E,A}$	F(1,7) = 182.8	p<0.000**	0.963
$p_{PE,PS} = 0.717 \cdot p_{PRO,PRO} \cdot p_{E,S}$	F(1,7) = 333	p<0.000**	0.979
$p_{PE,PE} = 0.413 \cdot p_{PRO,PRO} \cdot p_{E,E}$	F(1,7) = 11.92	p<0.050*	0.630
$p_{PE,SA} = 0.514 \cdot p_{PRO,SOL} \cdot p_{E,A}$	F(1,7) = 43.75	p<0.001**	0.862
$p_{PE,SS} = 1.048 \cdot p_{PRO,SOL} \cdot p_{E,S}$	F(1,7) = 9.729	p<0.050*	0.582
$p_{PE,SE} = 0.785 \cdot p_{PRO,SOL} \cdot p_{E,E}$	F(1,7) = 19.11	p<0.005**	0.732

* p<0.05 ** p<0.01

Table 5.2 Linear regression models of sequences of two ASE design operations within and in-between problem and solution space (continued)

Equation (including coefficient)	F-statistic	p-value	R^2
$p_{SA,PA} = 1.578 \cdot p_{SOL,PRO} \cdot p_{A,A}$	$F(1,7) = 60.16$	$p<0.001$**	0.896
$p_{SA,PS} = 1.156 \cdot p_{SOL,PRO} \cdot p_{A,S}$	$F(1,7) = 38.44$	$p<0.001$**	0.846
$p_{SA,PE} = 0.157 \cdot p_{SOL,PRO} \cdot p_{A,E}$	$F(1,7) = 8.3$	$p<0.050$*	0.543
$p_{SA,SA} = 0.876 \cdot p_{SOL,SOL} \cdot p_{A,A}$	$F(1,7) = 473.4$	$p<0.000$**	0.985
$p_{SA,SS} = 0.896 \cdot p_{SOL,SOL} \cdot p_{A,S}$	$F(1,7) = 506.4$	$p<0.000$**	0.986
$p_{SA,SE} = 1.121 \cdot p_{SOL,SOL} \cdot p_{A,E}$	$F(1,7) = 872.7$	$p<0.000$**	0.992
$p_{SS,PA} = 0.844 \cdot p_{SOL,PRO} \cdot p_{S,A}$	$F(1,7) = 57.01$	$p<0.001$*	0.891
$p_{SS,PS} = 0.953 \cdot p_{SOL,PRO} \cdot p_{S,S}$	$F(1,7) = 142.7$	$p<0.000$**	0.953
$p_{SS,PE} = 0.140 \cdot p_{SOL,PRO} \cdot p_{S,E}$	$F(1,7) = 2.73$	$p>0.050$	0.281
$p_{SS,SA} = 1.129 \cdot p_{SOL,SOL} \cdot p_{S,A}$	$F(1,7) = 1441$	$p<0.000$**	0.995
$p_{SS,SS} = 0.975 \cdot p_{SOL,SOL} \cdot p_{S,S}$	$F(1,7) = 220.8$	$p<0.000$**	0.969
$p_{SS,SE} = 1.103 \cdot p_{SOL,SOL} \cdot p_{S,E}$	$F(1,7) = 712.6$	$p<0.000$**	0.990
$p_{SE,PA} = 1.716 \cdot p_{SOL,PRO} \cdot p_{E,A}$	$F(1,7) = 40.96$	$p<0.001$**	0.854
$p_{SE,PS} = 1.595 \cdot p_{SOL,PRO} \cdot p_{E,S}$	$F(1,7) = 28.83$	$p<0.005$**	0.805
$p_{SE,PE} = 0.452 \cdot p_{SOL,PRO} \cdot p_{E,E}$	$F(1,7) = 1.34$	$p>0.050$	0.161
$p_{SE,SA} = 0.977 \cdot p_{SOL,SOL} \cdot p_{E,A}$	$F(1,7) = 658.7$	$p<0.000$**	0.990
$p_{SE,SS} = 0.967 \cdot p_{SOL,SOL} \cdot p_{E,S}$	$F(1,7) = 279.5$	$p<0.000$**	0.976
$p_{SE,SE} = 1.141 \cdot p_{SOL,SOL} \cdot p_{E,E}$	$F(1,7) = 152.5$	$p<0.000$**	0.956

* $p<0.05$ ** $p<0.01$

The 36 regression equations enable myriads of investigations to be performed and are, as such, particularly valuable addition to the mathematical model. Among other things, the response provided by the equations can be used to perform moving average analysis of ASE design operations sequences within and in-between the problem and the solution space, as shown in Figures 4.13 and 4.14. Nevertheless, the Shapiro-Wilk test rejected the assumption of normality for a total of eight design operations sequences ($p_{PA,SA}$, $p_{PA,SS}$, $p_{PS,PS}$, $p_{PE,PS}$, $p_{PE,PE}$, $p_{SS,PE}$, $p_{SE,PS}$, $p_{SE,PE}$). These regression models have thus not been directly implemented in the mathematical model. The ability of the formulated regression models to replicate the most important sequences of design operations, captured in the protocol analysis study, is investigated in the following section.

5.3. Mathematical model testing

The formulated linear regression equations enable prediction of average proportions of design operations and their sequences within a design activity or part of the design activity, based on the average proportions of analysis, synthesis and evaluation, and problem- and solution-related design operations during that period. Their integration in the theoretical framework proposed in Chapter 3 allows the formulation of a mathematical model for calculating proportions of design operations and their sequences based on the three input parameters (two to define proportions of ASE and one to define proportions of problem/solution-related design operations).

The mathematical model has thus been designed to rely both on the regression equations with a high goodness of fit (high R^2 values), which do not violate the normality of residuals assumption (based on the Shapiro-Wilk test), as well as the theoretical foundations of state-transitions proportions and sequences proposed in Tables 3.2 and 3.3. For example, regarding proportions of design operations, solution analysis, synthesis and evaluation exhibit higher R^2 values when compared to problem analysis, synthesis and evaluation. Hence, according to Table 3.2, problem analysis, synthesis and evaluation can be defined as shown in Equations 5.25, 5.26 and 5.27.

$$p_{\mathrm{PA}} = p_{\mathrm{A}} - p_{\mathrm{SA}} \quad \text{(Equation 5.25)}$$

$$p_{\mathrm{PS}} = p_{\mathrm{S}} - p_{\mathrm{SS}} \quad \text{(Equation 5.26)}$$

$$p_{\mathrm{PE}} = p_{\mathrm{E}} - p_{\mathrm{SE}} \quad \text{(Equation 5.27)}$$

In this way, the high goodness of fit of solution-related design operation is utilised to improve the prediction ability of problem-related design operations. Moreover, such formulation ensures that the resulting proportions of ASE precisely correspond to the input parameters.

Similarly, it can be argued that for a protocol string with a sufficient number of design operation instances, the following expressions apply (Equations 5.28, 5.29, 5.30, 5.31 and 5.32):

$$p_{\mathrm{A}} = p_{\mathrm{A,A}} + p_{\mathrm{A,S}} + p_{\mathrm{A,E}} = p_{\mathrm{A,A}} + p_{\mathrm{S,A}} + p_{\mathrm{E,A}} \quad \text{(Equation 5.28)}$$

$$p_{\mathrm{S}} = p_{\mathrm{S,A}} + p_{\mathrm{S,S}} + p_{\mathrm{S,E}} = p_{\mathrm{A,S}} + p_{\mathrm{S,S}} + p_{\mathrm{E,S}} \quad \text{(Equation 5.29)}$$

$$p_{\mathrm{E}} = p_{\mathrm{E,A}} + p_{\mathrm{E,S}} + p_{\mathrm{E,E}} = p_{\mathrm{A,E}} + p_{\mathrm{S,E}} + p_{\mathrm{E,E}} \quad \text{(Equation 5.30)}$$

$$p_{\mathrm{PRO}} = p_{\mathrm{PRO,PRO}} + p_{\mathrm{PRO,SOL}} = p_{\mathrm{PRO,PRO}} + p_{\mathrm{SOL,PRO}} \quad \text{(Equation 5.31)}$$

$$p_{\mathrm{SOL}} = p_{\mathrm{SOL,PRO}} + p_{\mathrm{SOL,SOL}} = p_{\mathrm{PRO,SOL}} + p_{\mathrm{SOL,SOL}} \quad \text{(Equation 5.32)}$$

Namely, the proportion of a particular design operation is equal to the sum of proportions of all design operations sequences starting with that specific design operation, but also to the sum of proportions of all design operations sequences ending with that design operation. Such argumentation is vital as it allows taking advantage of only the regression equations with the highest prediction ability.

Hence, the resulting set of equations encompassed within the mathematical model results either from regression modelling or from the theoretical assumptions. The mathematical model developed in such a way was first employed to compute moving average proportions of design operations and sequences of design operations for a given average ASE and problem/solution proportions. Namely, to test the prediction ability of the developed mathematical model, the input parameters have been sampled from the moving average proportions of ASE and problem/solution-related design operations obtained from the protocol analysis study of team conceptual design activities.

The predictive power of the model was tested by plotting graphs of moving average proportions corresponding to those reported in Figures 4.9-4.13. Only three predicated independent variables have been sampled from the original dataset (proportions of analysis, synthesis and problem-related design operations). The mathematical model utilises these three independent variables from the observed moving average data to compute (predict) proportions of design operations and their sequences for these particular moving average windows. The resulting graphs concerning the proportions of ASE design operations within the problem and the solution space are shown in Figure 5.4. The graphs concerning the proportions of sequences of two ASE design operations are shown in Figure 5.5. Finally, the graphs concerning the proportions of sequences of two design operations related to either problem or solution space are shown in Figure 5.6.

A qualitative comparison reveals a high level of resemblance between the observation-based Figures 4.9, 4.11 and 4.12, and the simulation-based Figures 5.4, 5.5 and 5.6. Notably, it can be argued that the simulated proportions coincide with the descriptions of the teams' processes provided in Subsection 4.3.3. The change in proportions of design operations and their sequences, which have been identified for each of the teams, have been satisfactorily replicated using the formulated mathematical model. Since the conceptualisation of the mathematical model as a support tool is to provide insights regarding the patterns and trends in performing particular design operations, rather than precise percentages, the model has been validated as appropriate for further research steps.

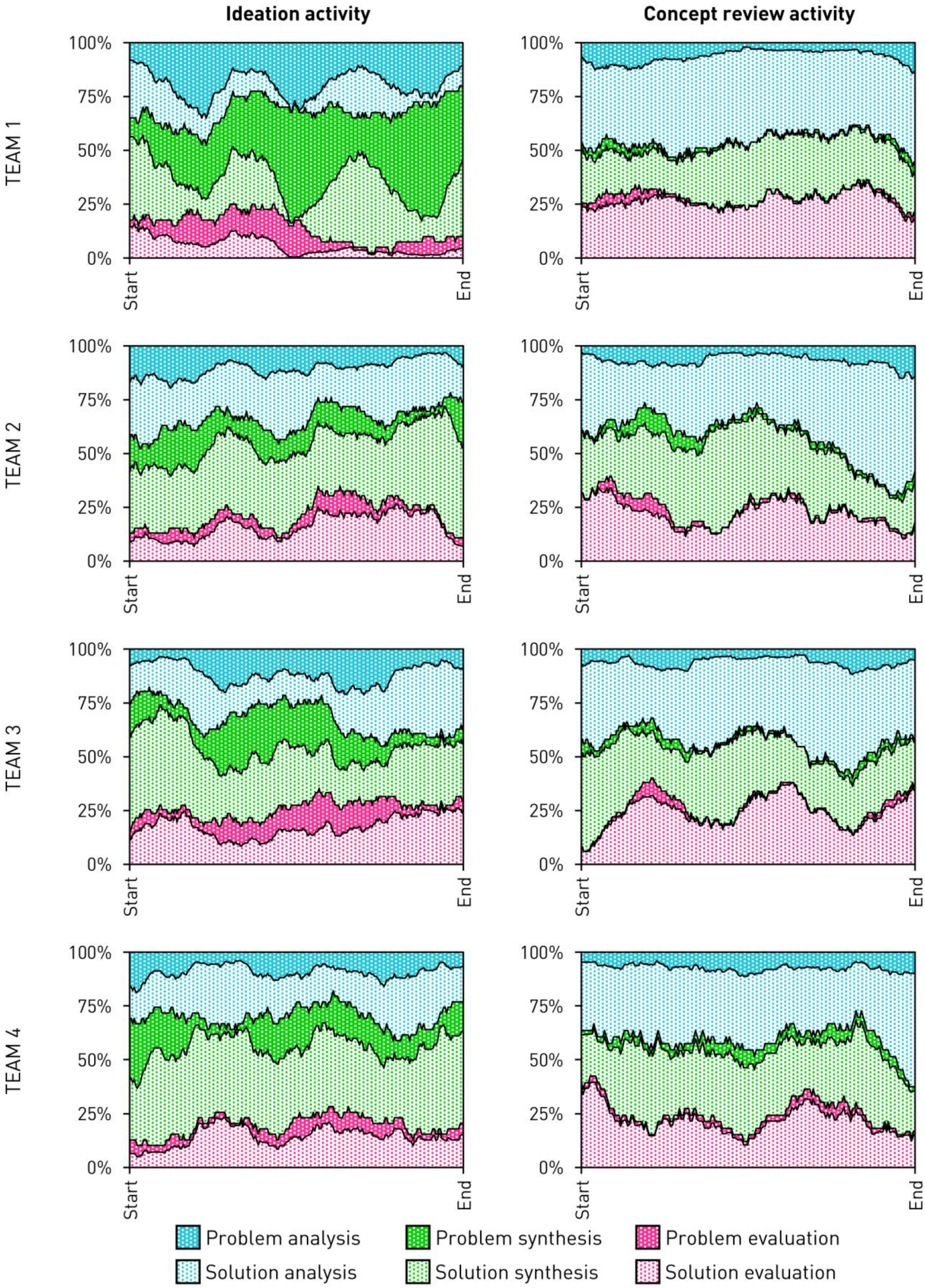

Figure 5.4 Overview of simulated moving average proportions of design operations with input parameters based on observed ideation and concept review activities

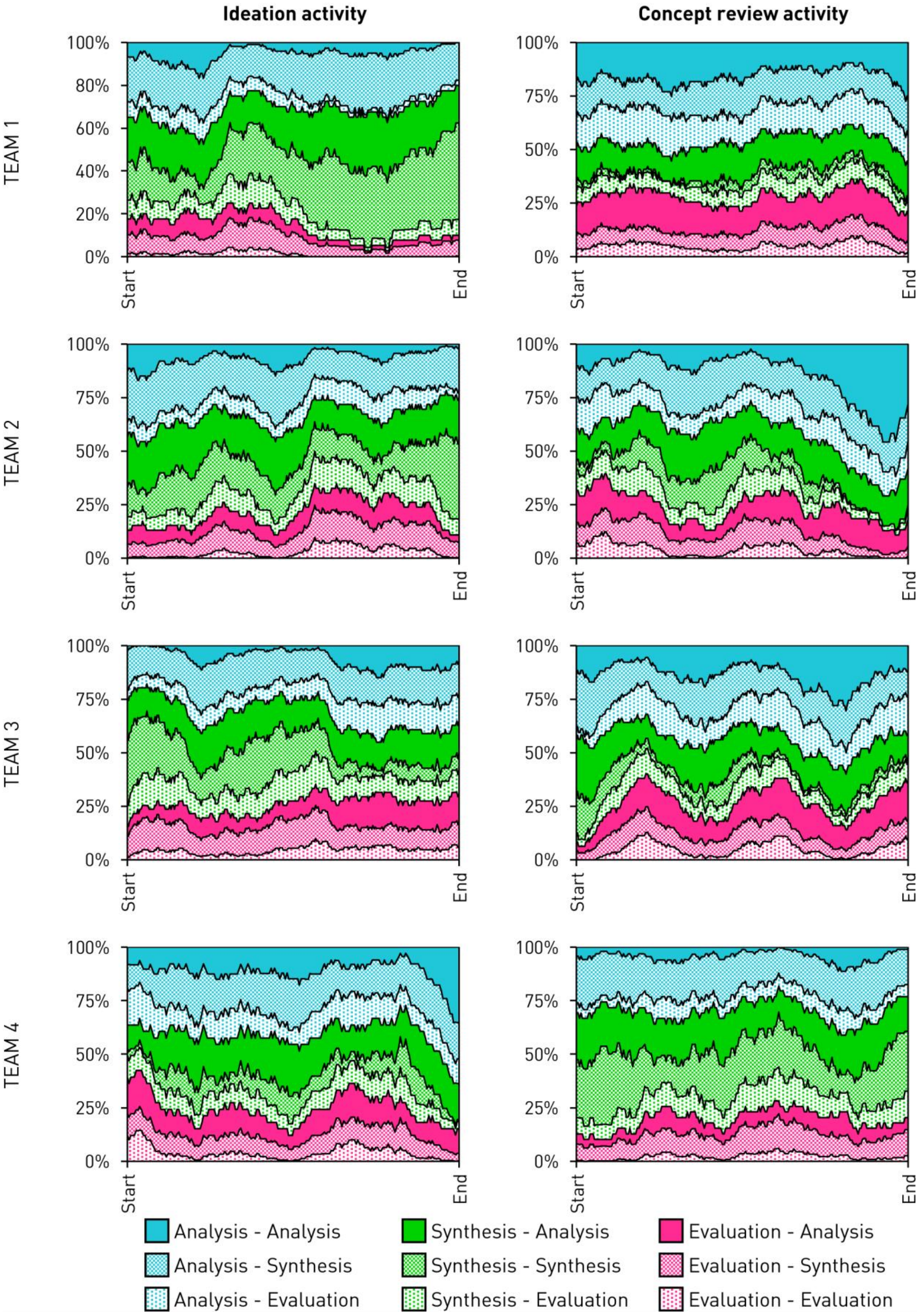

Figure 5.5 Overview of simulated moving average proportions of sequences of ASE with input parameters based on observed ideation and concept review activities

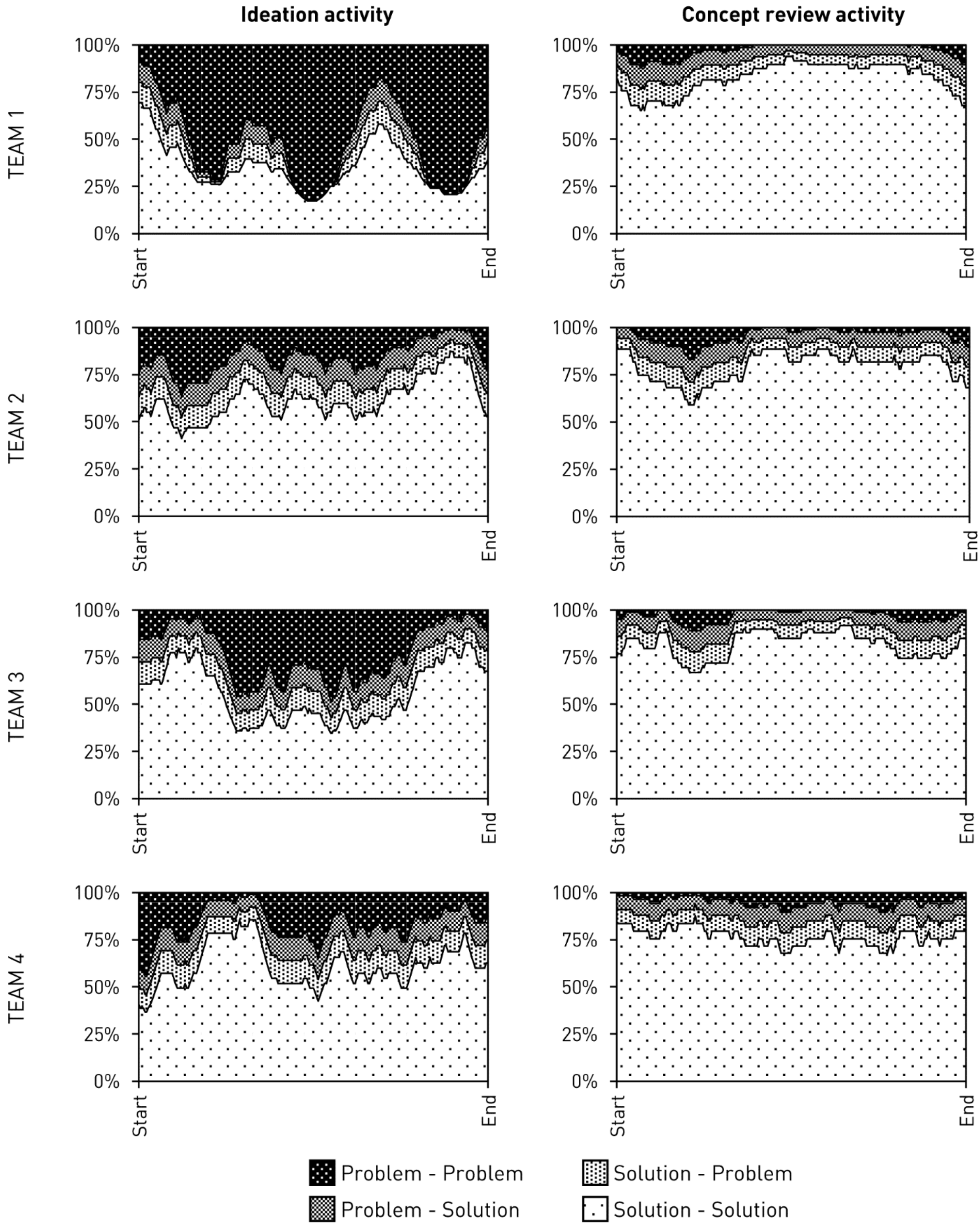

Figure 5.6 Overview of simulated moving average proportions of sequences of problem- and solution-related design operations with input parameters based on observed ideation and concept review activities

Finally, a comparison can be made for sequences of unaggregated design operations (ASE within and in-between the problem and the solution space). Again, due to a large number of combinations of observed experimental sessions and sequences of two design operations, only one example per team is here reported (Figure 5.7).

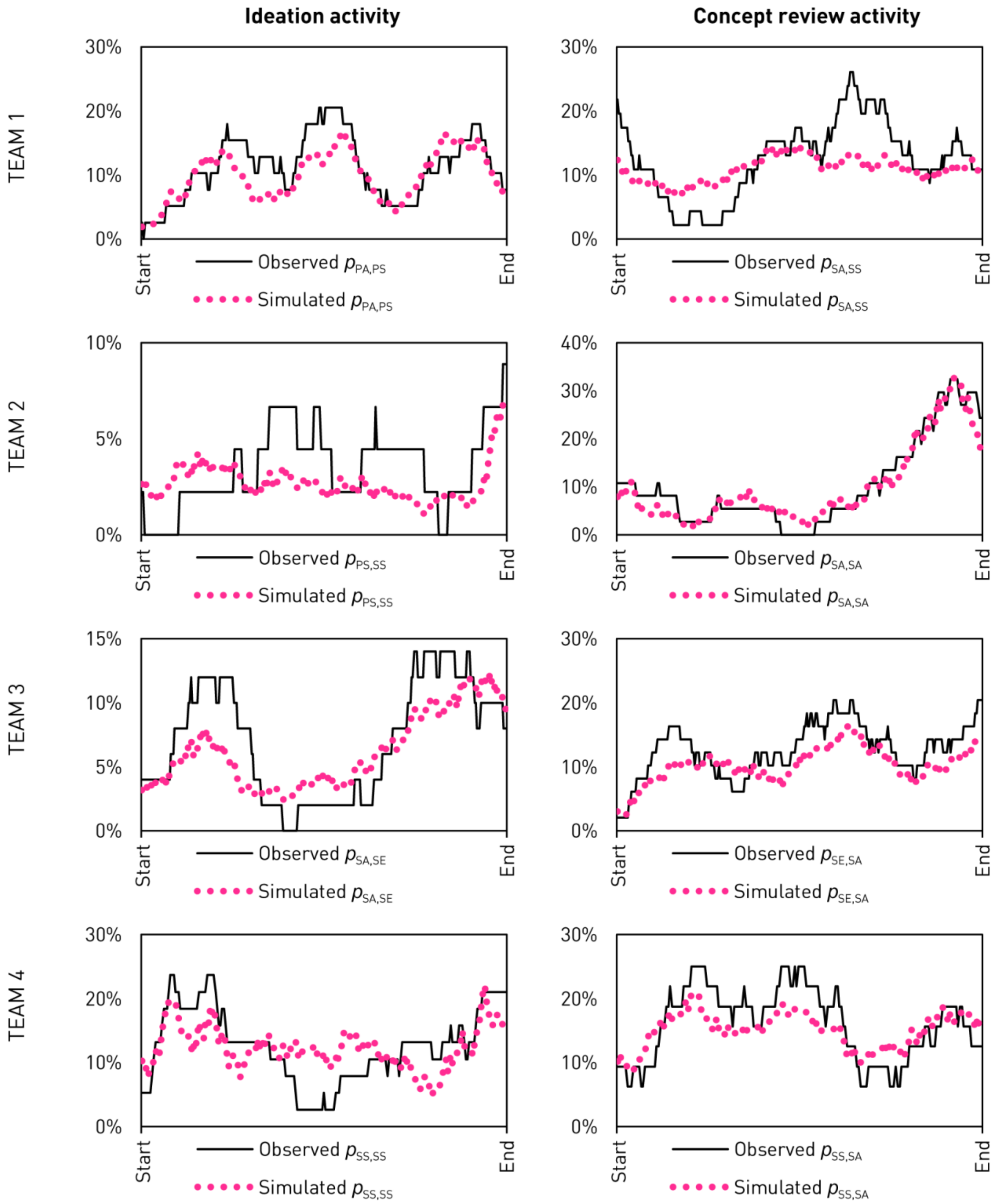

Figure 5.7 Overview of simulated moving average proportions of sequences of ASE design operations within and in-between problem and solution space, and with input parameters based on observed ideation and concept review activities

Each of the examples represents the moving average proportion of a distinctive sequence which exhibited high proportions during the observed activities. The lower fit of the regression models is noticeable, particularly for sequences which have rarely appeared during the protocol analysis study. Also, the regression models fail to reflect the spikes precisely, that is the major changes in moving average proportions of certain design operations sequences appearing in-between a relatively small number of protocol segments. Nevertheless, the changes in proportions of sequences have to a large degree been satisfactorily replicated using the mathematical model.

6. COMPUTATIONAL STUDY

The sixth chapter reports on the second experimental study. The mathematical model formulated in the previous chapter is here utilised as a means of simulating proportions and sequences of design operations, based on a predefined team conceptual design process. A computational tool has been developed for this purpose, and a computational study has been set up in order to investigate the effects of design novelty and the progress of conceptual design stage on the team conceptual design activity process. The approach to the analysis of simulated protocols is based on the protocol analysis reported in the fourth chapter.

The mathematical model developed in Chapter 5 transforms any given proportion of ASE and the ratio of the problem- and solution-related design operations into proportions of ASE design operations within and in-between the problem and the solution space, as well as proportions of moves between two of such design operations. In this chapter, the predictive power of the mathematical model is utilised to simulate sequences of design operations which are specific for team conceptual design of technical systems. In order to conduct such experimental studies, a computational tool which utilises the mathematical model has been developed.

The computational tool and the integrated mathematical model enable simulations of scenarios outside the scope covered with the protocol analysis study reported in Chapter 4. More precisely, it enables analysis of design operation patterns which result from proportions of ASE and problem/solution space ratios different from those observed in the first experimental study. This ability allows addressing the research question RQ5, which concerns identifying the differences in the way teams perform design operations depending on the novelty of the technical system being designed. Of particular research interest is identifying the differences in conceptual design information processing of the adaptive versus innovative design projects. Insights from the literature review reported across Sections 2.1-2.3 have been used to set up the overall features of the process expected during the conceptual design stage of technical systems development.

The tool developed for conducting the computational study is described in Section 6.1. The adaptive and innovative setups for the computational study of the conceptual design are described in Section 6.2. Finally, in Section 6.3, the simulated protocols are analysed in terms of design operation proportions and sequences.

6.1. Computational tool

An Excel-based computational tool has been developed to enable efficient utilisation of the mathematical model as a means of simulating information processing during team conceptual design activity. The computational tool facilitates predefinition of computational study parameters, running plentiful simulations of stochastic processes, and analysis of the resulting protocol strings. The description of the algorithm used to implement the mathematical model in the computational tool is shown in Figure 6.1.

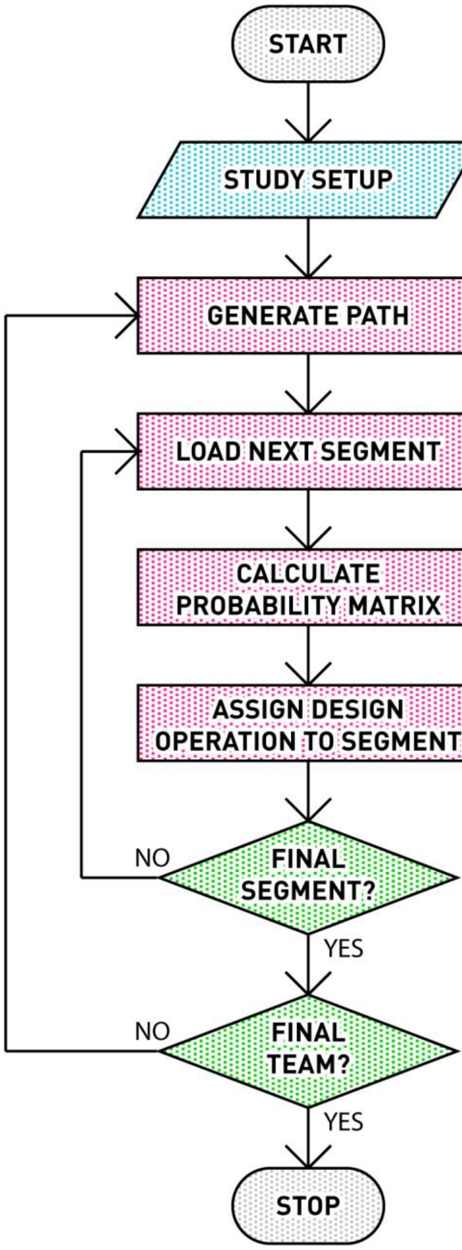

Figure 6.1 The algorithm used to implement the mathematical model for the computational study of team conceptual design process

The main steps within the algorithm can be described as follows:

1. **Study setup** – The user predefines several computational study parameters:

   First, the user defines the number of main steps within the conceptual design process and assigns each of the steps with a particular proportion of ASE and problem/solution-related design operations. Hence each step is assigned with proportions of analysis and synthesis (proportion of evaluation is calculated based on these two values) and a proportion of problem-related design operations (proportion of solution-related design operations is also automatically calculated). These predefined steps reflect the sequences of tasks that are specific for the simulated conceptual design process. As such, the predefined steps account for adjusting the process in terms of proportions of design operations and their sequences as the simulation progresses. An example of predefining the conceptual design steps is shown in Figure 6.2.

   Second, the user defines the number of simulations to be run (number of teams simulated) and the minimal number of segments per simulation (design operations performed by the team). The minimal number of segments corresponds to the number of different design operations performed in case there is no iteration during the process. As a reference, the number of design operation segments observed in experimental studies (Chapter 4) was on average 293 for ideation and 280 for concept review activity. In its simplest sense, the implication of the predefined steps and the associated number of segments appears in direction and amplitude (segments needed in between the steps) of change in ASE and problem/solution proportions throughout the simulated activity, in the case of no uncertainty and no iteration.

STEP	p_A	p_S	p_E	p_{PRO}	p_{SOL}
S1	60%	30%	10%	60%	40%
S2	35%	50%	15%	40%	60%
S3	10%	60%	30%	20%	80%
S4	40%	20%	40%	30%	70%
S5	35%	40%	25%	15%	85%

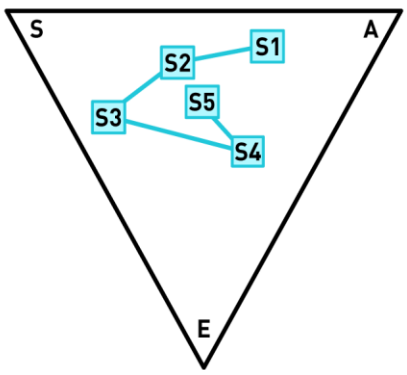

Figure 6.2 An example of defining the conceptual design process path using proportions of ASE design operations in steps S1, S2, S3, S4 and S5 (the proportions displayed within the columns are automatically calculated)

Finally, the user predefines also the probability of iteration and level of uncertainty (both in percent) since these two phenomena have been found important for distinguishing adaptive and innovative design within the literature review. Implications of iteration and uncertainty are explained in the following algorithm step. As shown in Figure 6.1, study setup is the only algorithm step where the user must provide input parameters.

2. **Generate path** – The progress of the conceptual design stage stems from the predefined steps and the assigned proportions of ASE and problem/solution ratio (as described in the study setup algorithm step). The algorithm linearly adjusts the proportions of design operations in-between the predefined steps of the conceptual design process, thus building initial linear paths between the steps (as shown using the triangular proportion visualisation in Figure 6.2). Additionally, the total number of predefined protocol segments is equally distributed across the designated process path. The linear path and the number of segments along the path are then subject to changes based on the predefined levels of iteration and uncertainty. Namely, iteration and uncertainty are conceptualised as distortions of the linear progress.

   In the context of here presented research, iteration is defined as a probability of returning to a previous point in the process (repeating design operations). Before moving from one design operation to another (from one segment to another), the probability of iteration is compared to a randomly generated number (number between 0 and 1, that is 0 % and 100%). If the random number is lower than the iteration probability, the process will continue at a random, previously visited combination of ASE proportions (for the purpose of here presented computational study, the process went back up to 15 path steps, which is currently a provisionally set value).

   Uncertainty distorts the vector length r and angle δ (Figure 3.6) assigned to the proportions of ASE in the current process. The vector's length is modified based on the inverse of the normal cumulative distribution for the predefined vector length and a standard deviation. The standard deviation defines the level of uncertainty – the higher the standard deviation, the higher the probability that the vector length will be more distorted. The same procedure is then repeated with the angle of the vector and the proportion of problem-related design operations. Once the vector is distorted, the proportions of ASE design operations are recalculated.

   The effect of various levels of iteration and uncertainty on the progress of the simulated conceptual design is illustrated by plotting exemplary paths (series of segments) within the triangular visualisation of ASE proportions, as shown in Figure 6.3.

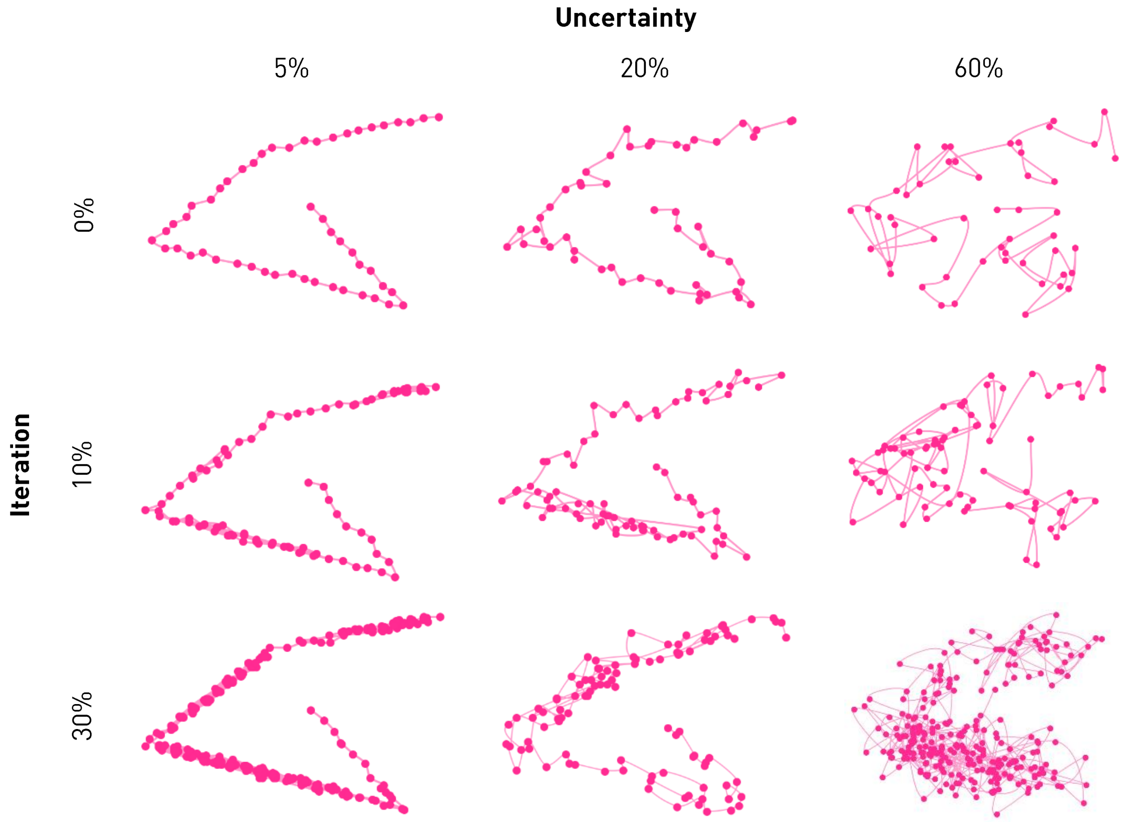

Figure 6.3 The effect of different levels of iteration and uncertainty on the conceptual design process path

3. **Load next segment** – Once the path has been generated and the final number of segments is known (the predefined number of segments + iteration), the simulation will move from one generated segment to another and load the proportions of ASE and problem- and solution-related design operations assigned to each of these segments (based on their position on the path). This cycle is repeated until the last generated segment is reached, as shown in Figure 6.1.
4. **Calculate probability matrix** – After loading the ASE and problem/solution proportions assigned to a particular segment, the regression equations introduced in Section 5.2 are used to calculate (predict) proportions of sequences of ASE design operations within and in-between the problem and the solution space. Thus, given any set of segments containing average proportions of ASE (e.g. paths visualised in triangular proportion visualisation as shown in Figure 4.10), and the corresponding problem/solution ratios, the expected proportions of design operations and their sequences are computed. These proportions are transformed into probabilities of moves between design operations (within a probability matrix), as proposed in Equation 3.4 and Tables 3.4 and 3.5 within the theoretical framework (Chapter 3).

5. **Assign design operation to segment** – The computed probability matrix is used to generate the next design operation based on the current one. The following design operation is thus selected by emulating a stochastic process (a random number is generated and compared to the probabilities in the transition matrix). When the following design operation is selected, it is written down in the protocol string, and the simulation process continues to the next segment.

Algorithm steps 3, 4 and 5 are repeated for every segment of the predefined path. The generation of protocol instances (segments assigned with a design operation) continues until the number of path segments reaches the predefined number (path segments repeated through iteration are not counted). Algorithm step 2 is repeated for every new team simulated (number of teams simulated corresponds to the number of simulations predefined in the first algorithm step). An example of the simulation procedure is shown in Figure 6.4.

		A	S	E	PRO	SOL
STEP	1	60%	30%	10%	60%	40%
	2	35%	50%	15%	40%	60%
	3	10%	60%	30%	20%	80%
	4	40%	20%	40%	30%	70%
	5	35%	40%	25%	15%	85%

PATH STEPS	ITERATION PROBABILITY	UNCERTAINTY LEVEL
200	5%	30%

TOTAL STEPS	TOTAL ITERATIONS	WINDOW SIZE
280	11	15%

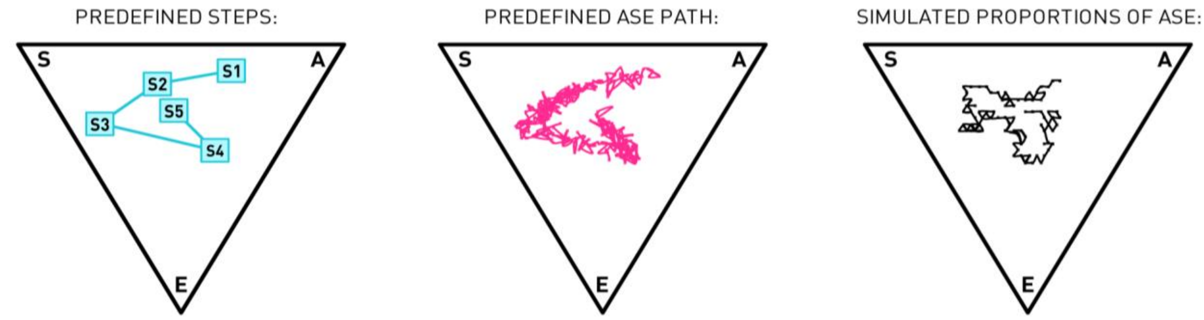

Figure 6.4 Simulation procedure example: triangular visualisations include predefined conceptual design steps, predefined ASE path which defines transition probabilities, and actual simulated proportions of ASE

The three triangular visualisations in Figure 6.4 represent (from left to right): the linear path of ASE proportions between the predefined conceptual design steps, the distortion of the predefined path due to iteration and uncertainty, and the stochastically simulated path based on the strings of design operations assigned to the predefined segments.

6.2. Computational study setup

The overall structure of the simulated conceptual design process has been developed based on the information-processing decomposition of the conceptual design stage as found within the prescriptive models of engineering design. The rationale for utilising systematic design guidelines for predefining the conceptual design process stems from the argument that prescriptive design methodologies, such as the Systematic Approach by Pahl and Beitz can, to some degree, be employed as predictive models of engineering design. Namely, Kannengiesser and Gero [276] report that although the Systematic Approach is generally seen as a prescriptive model of designing, it can be used to predict some (although not all) of students' designing behaviour.

The overview of information processes associated with the conceptual design stage has been provided in Section 2.2. Five conceptual design steps (Table 6.1) have been defined in terms of prevailing types of design operations, analogously to the problem-solving steps prescribed in Table 2.5 and described throughout the Subsection 2.2.2: problem formulation, solution search, solution generation, solution evaluation and solution refinement.

Table 6.1 Prevailing types of design operations for the predefined conceptual design steps in the computational study

COMPUTATIONAL STUDY STEPS	PRESCRIPTIVE DESIGN STEPS	PREVAILING DESIGN OPERATIONS	
		ASE	PROBLEM/SOLUTION
S1 Problem formulation	**Function structure development**	Analysis and synthesis	Problem-solution co-evolution
S2 Solution search	**Working principles search**		
S3 Solution generation	**Concept generation**	Synthesis	Solution space
S4 Solution evaluation	**Concept evaluation**	Analysis and evaluation	Problem and solution space
S5 Solution refinement	**Concept selection and refinement**	Synthesis and evaluation	Problem and solution space

Problem formulation concerns analysis of the existing requirements and formulation of new ones, whereas teams simultaneously search for new solutions as part of the problem-solution co-evolution process. Solution generation involves primarily the synthesis design operation within the solution space, solution evaluation concerns gaining understanding of solution entities and evaluating them against the entities of the problem space. Finally, during the last step, teams refine the selected solution and conduct the final evaluation of its elements.

Each of the steps can be further assigned to the distinctive characteristics of adaptive and innovative design. The overview of phenomena relevant for innovative and adaptive design and how they are interpreted and implemented in the context of state transition using ASE design operations within and in-between the problem and the solution space is shown in Table 6.2.

Table 6.2 Overview of phenoma related to adaptive and innovative design and how they have been interpreted and implemented in the context of the computational study

PHENOMENA	ADAPTIVE DESIGN		INNOVATIVE DESIGN	
	Literature	Implementation	Literature	Implementation
Uncertainty [44], [188]	Medium	**Medium deviation** from the planned path within the triangular proportion visualisation	Large	**High deviation** from the planned path within the triangular proportion visualisation
Iteration [139]	Less	**Lower iteration probability** within the planned path	More	**Higher iteration probability** within the planned path
Function decomposition [41]	Existing solutions	Higher proportions of **solution analysis**	Abstract problem formulation	Higher proportions of **problem synthesis**
Use of existing solution elements [185]	Reuse of priori solution elements	Higher proportions of **solution evaluation**	No or little priori solutions elements	Higher proportions of **solution synthesis**
Proficiency of evaluation criteria usage [8]	Higher	Higher proportions of **solution evaluation**	Lower	Lower proportions of **solution evaluation**
Nature of design space exploration [149]	Less exploratory	Lower proportions of **synthesis**	More exploratory	Higher proportions of **synthesis**
Customer-driven development [149]	More	Higher proportions of **problem analysis**	Less	Higher proportions of **problem synthesis and evaluation**
Dominant type of reasoning [189]	Inductive reasoning	Higher proportions of **evaluation**	Abductive reasoning	Higher proportions of **synthesis**

The literature insights on the listed phenomena are conceptualised as guidelines for the scope of the parameters used for calculating the moving average proportions of design operations and their sequences. For example, as shown in Tables 2.3 and 2.6, the innovative (original/radical) design is characterised by more iteration, fuzzy front-end activities, lower proficiency in using evaluation criteria, more exploration, no or little prior given solution elements, as well as higher levels of conceptual design uncertainty. On the other hand, the adaptive (incremental) design is characterised by more process flexibility, abbreviated front-end activities, higher proficiency of evaluation criteria usage, more customer-driven development and partial reuse of prior solutions. Innovative design is related to abductive design processes and design synthesis, whereas adaptive design is related to inductive design processes and design evaluation. In addition, innovative designs are based on requirements lists and abstract problem formulation, whereas adaptive designs are based on the analysis of existing solutions.

Each characteristic affects the predefined proportions of ASE and problem/solution-related design operations, as well as the structure of the conceptual design process when visualised using the triangular proportion visualisation. An overview of the exact mechanisms used to implement and simulate the characteristics has been described in the previous section.

6.2.1. Adaptive design computational study setup

The input parameters for the computational study of adaptive conceptual design are reported in Table 6.3. Overall, the iteration probability is set to low (5%), and the uncertainty level is set to medium (40%). Problem formulation is associated with high proportions of analysis and problem-related design operations since it is more customer driven (analysis of given requirements).

Table 6.3 Overview of input parameters for adaptive design computational study (p_E is derived from p_A and p_S, and p_{SOL} is derived from p_{PRO})

STEP	p_A	p_S	p_E	p_{PRO}	p_{SOL}	ITERATION PROBABILITY	UNCERTAINTY LEVEL
S1 Problem formulation	60%	30%	10%	60%	40%	5%	40%
S2 Solution search	50%	40%	10%	30%	70%		
S3 Solution generation	30%	45%	25%	15%	85%		
S4 Solution evaluation	35%	15%	50%	30%	70%		
S5 Solution refinement	40%	35%	25%	20%	80%		

Solution search is characterised by a high proportion of analysis within the solution space (analysis of existing solutions) and relatively low proportions of synthesis (not explorative). The proportions of solution synthesis and evaluation increase during solution generation, as it relies on combining existing and familiar solutions. Solution evaluation is defined using high proportions of evaluation and an even proportion of problem and solution-related design operations (higher proficiency of evaluation criteria usage, inductive reasoning). Finally, the solution refinement step exhibits relatively high proportions of solution synthesis and evaluation.

6.2.2. Innovative design computational study setup

The input parameters for the computational study of innovative conceptual design are reported in Table 6.4. The iteration probability and uncertainty level are significantly higher (10% and 80% respectively) when compared to the adaptive design setup. Since problem formulation is less customer-driven, the first step is associated with more similar proportions of analysis, synthesis and evaluation, as teams need to analyse the given problem but also formulate and evaluate new requirements. In addition, the proportions of the problem-related design operations are set higher, as co-evolution is expected due to the more exploratory nature of the innovative design process.

Table 6.4 Overview of input parameters for innovative design computational study (p_E is derived from p_A and p_S, and p_{SOL} is derived from p_{PRO})

STEP	p_A	p_S	p_E	p_{PRO}	p_{SOL}	ITERATION PROBABILITY	UNCERTAINTY LEVEL
S1 Problem formulation	45%	35%	20%	70%	30%	10%	80%
S2 Solution search	25%	60%	15%	40%	60%		
S3 Solution generation	30%	45%	25%	25%	75%		
S4 Solution evaluation	35%	25%	40%	40%	60%		
S5 Solution refinement	35%	45%	20%	30%	70%		

Solution search is characterised by exploration, and higher proportions of synthesis, particularly within the solution space as no or little prior given solution elements are used. The relatively high proportion of synthesis and problem-related design operations (due to abstract problem formulation and more exploratory nature of design space exploration) slowly declines towards solution generation. Solution evaluation has a relatively low proportion of evaluation when compared to adaptive processes, due to lower proficiency in using evaluation criteria. Solution refinement step is defined similarly to the adaptive design, with higher proportions of synthesis and problem-related design operations.

The setup of the levels of uncertainty and iteration used in simulations of adaptive and innovative design was trial-and-error based. Namely, no explicit data support could be found in the reviewed literature, hence the parameter definition was guided primarily by investigating and replicating the deviations exhibited in the protocol analysis studies (see, e.g. Figure 4.10 in Chapter 4).

6.2.3. Comparison of adaptive and innovative computational study setups

A visual comparison of ASE proportions within the five predefined conceptual design steps of the adaptive and innovative computational study is shown in Figure 6.5. It is important to highlight that real-world adaptive and innovative design processes may exhibit significantly different proportions of design operations than described in Tables 6.3 and 6.4. The provisionally selected values are based primarily on the characteristics that the design process is likely to inherit from the novelty level of the technical system being developed, and which have been identified in the conducted literature review. The proportions are also based on the proportions identified in the protocol analysis study, primarily by relating solution search to ideation activity and solution evaluation and refinement to concept review activity.

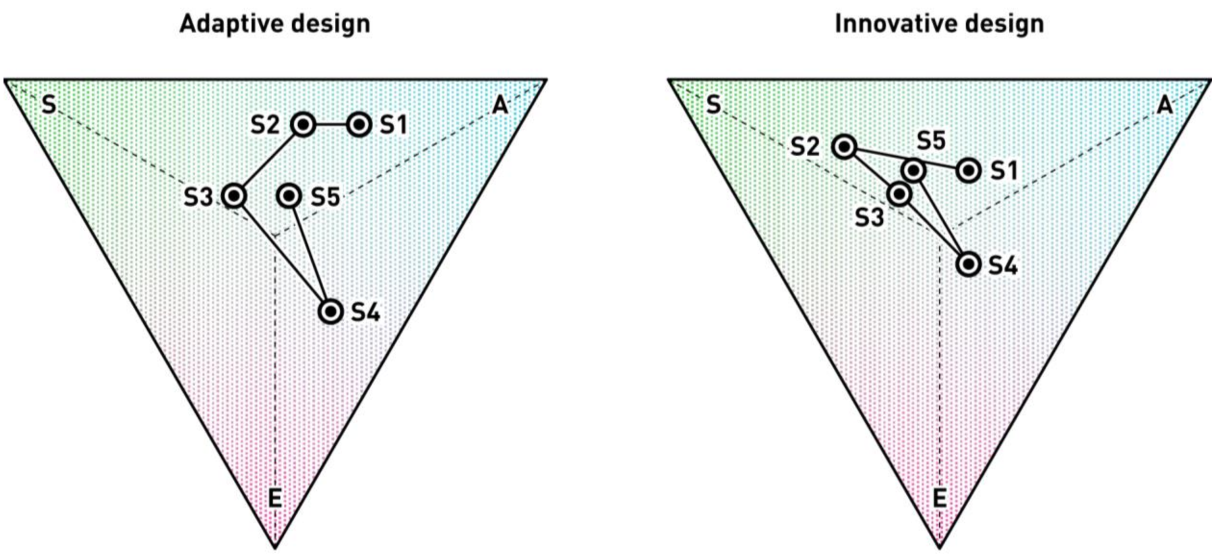

Figure 6.5 Triangular visualisation of ASE design operation proportions for the predefined steps of the adaptive and innovative conceptual design process simulation

It is assumed that the selected values of input parameters will induce distinctive patterns of change in proportions and sequences of design operations when comparing adaptive and innovative design.

6.3. Computational study results

Similar to the protocol analysis study, the outputs of the computational simulations have been analysed in terms of proportions of design operations and their sequences, and how these proportions change with the progress of the five predefined conceptual design steps (tasks). The results of the adaptive and innovative conceptual design simulations are from here on regarded as adaptive and innovative design processes. An explorative computational experiment study was conducted. Both the adaptive and innovative conceptual design setups were simulated 100 times, with the predefined number of segments (without iteration) set to 300 and the first design operation set to "problem analysis" (supposing that it is the first design operation that teams perform when given the design brief).

On average, 541 (SD=73) segments have been simulated per team during adaptive design, and 1734 (SD=687) per team during innovative design. Hence, the higher iteration rate has resulted in a significant increase in the number of segments performed during the innovative conceptual design. The absolute frequencies of each of the design operations and their aggregation to ASE problem-solution spaces during the two types of processes are available in Table 6.5.

Table 6.5 Absolute frequencies of instances of protocol codes during simulations of adaptive and innovative conceptual design process

FREQUENCY VARIABLE	ADAPTIVE		INNOVATIVE	
	Mean	SD	Mean	SD
Problem analysis (n_{PA})	65.52	16.2	194.01	96.5
Problem synthesis (n_{PS})	42.09	10.6	204.96	96.7
Problem evaluation (n_{PE})	35.94	9.0	128.01	66.8
Solution analysis (n_{SA})	139.49	26.0	339.04	176.7
Solution synthesis (n_{SS})	129.5	23.4	467.48	233.6
Solution evaluation (n_{SE})	121.56	24.4	278.88	159.3
Analysis (n_A)	205.01	37.3	533.05	263.5
Synthesis (n_S)	171.59	30.3	672.44	322.1
Evaluation (n_E)	157.5	31.2	406.89	221.8
Problem-related (n_{PRO})	143.55	31.6	526.98	254.5
Solution-related (n_{SOL})	390.55	66.7	1085.4	560.6
Total of ASE in problem and solution space (n)	**521.47**	**72.7**	**1734.26**	**686.9**

Moreover, the effect of the iteration rate is also visible in the disproportionate increase in the standard deviation of instances assigned to each design operation. On average, the total number of segments has been 3.33 times higher for innovative design when compared to adaptive design, whereas the standard deviation of the total number of segments has been almost 10 times higher. Examples of the simulation segments in terms of change in ASE proportions are shown in Figure 6.6.

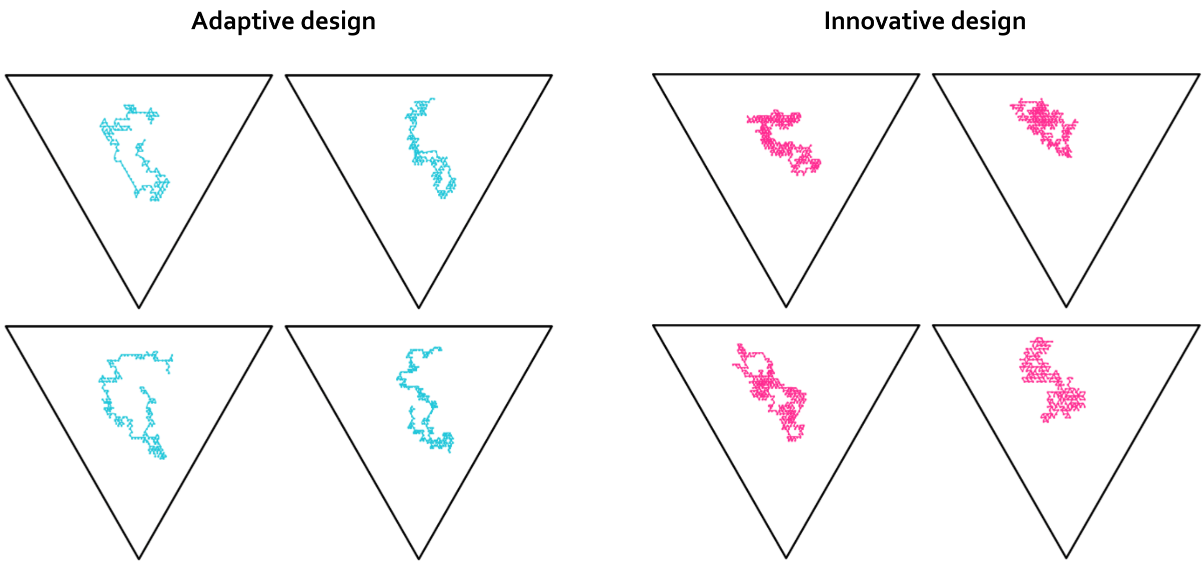

Figure 6.6 Examples of visualising the change in proportions of ASE for adaptive and innovative design simulations

6.3.1. Simulated proportions of design operations

The distributions of the counted instances (absolute frequencies) of design operations were normalised, so further analyses could be conducted using proportions of design operations. The resulting distributions of design operation proportions during adaptive and innovative conceptual design processes are shown in Table 6.6.

Table 6.6 Proportions of protocol codes obtained from adaptive and innovative conceptual design simulations

PROPORTION VARIABLE	ADAPTIVE		INNOVATIVE	
	Mean	SD	Mean	SD
Problem analysis (p_{PA})	0.123	0.020	0.122	0.027
Problem synthesis (p_{PS})	0.079	0.014	0.131	0.026
Problem evaluation (p_{PE})	0.067	0.011	0.079	0.013
Solution analysis (p_{SA})	0.261	0.018	0.208	0.019
Solution synthesis (p_{SS})	0.243	0.022	0.292	0.035
Solution evaluation (p_{SE})	0.228	0.024	0.168	0.032
Analysis (p_{A})	0.384	0.019	0.330	0.020
Synthesis (p_{S})	0.322	0.023	0.423	0.041
Evaluation (p_{E})	0.295	0.027	0.247	0.034
Problem-related (p_{PRO})	0.268	0.032	0.333	0.055
Solution-related (p_{SOL})	0.732	0.032	0.667	0.055

State-transition proportions during adaptive design

During the adaptive conceptual design process, the most frequent ASE design operation was analysis (on average 38% of all ASE design operations), followed by synthesis (32%), and evaluation (30%) as the least frequent. Of all design operations, on average 27% were performed in the problem space, and 73% in solution space. On average, the most frequent design operation in problem space was problem analysis (on average 46% of all design operations in problem space), followed by problem synthesis (29%) and problem evaluation (25%). The most frequent design operation in solution space was solution analysis (on average 36% of all design operations in solution space), followed by solution synthesis (33%) and solution evaluation (31%).

State-transition proportions during innovative design

The most frequent ASE design operation during the innovative conceptual design process was synthesis (on average 42% of all ASE design operations), followed by analysis (33%) and evaluation (25%) as the least frequent. Of all design operations, on average one third were performed in the problem space, and two thirds in the solutions space, which is a moderate change compared to the adaptive design process. On average, the most frequent problem-space design operation was problem synthesis (on average 53% of all design operations in problem space) followed by problem analysis (33%) and problem evaluation (14%). The order is the same within the solution space: solution synthesis was the most frequent (on average 44% of all design operations in solution space), followed by solution analysis (31%) and solution evaluation (25%).

Differences in state-transition proportions between ideation and concept review activities

A triangular proportion visualisation was again developed to qualitatively compare the average proportions of ASE during the adaptive and innovative design processes (enlarged parts of the visualisations are shown in Figure 6.7). These two simulation cases populated slightly different areas within the triangular visualisation, thus indicating gravitation towards distinctive proportions of design operations. During adaptive design, the proportions populated mainly the area around the triangle centre, with a slight shift towards analysis and synthesis (top). During innovative design, the proportions range from the centre towards the synthesis corner (top left).

Finally, the differences in proportions of ASE design operations within the problem and the solution space have been visualised using box plots (Figure 6.8). The box plots combine means and medians, quartiles, as well as minimum and maximum of the data and the outliers.

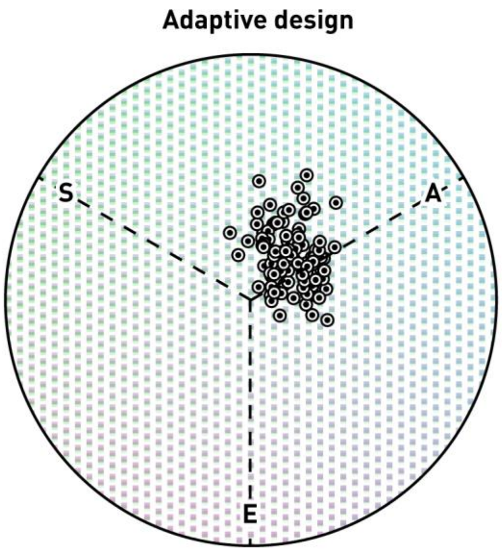

Figure 6.7 Visualisation of differences in average ASE proportions between all simulations of adaptive and innovative design

In general, the innovative design data exhibits broader interquartile ranges and more skewness (asymmetry of the probability distribution) when compared to the adaptive design data. This distinctive feature can be attributed to the higher uncertainty levels set prior to running the simulations.

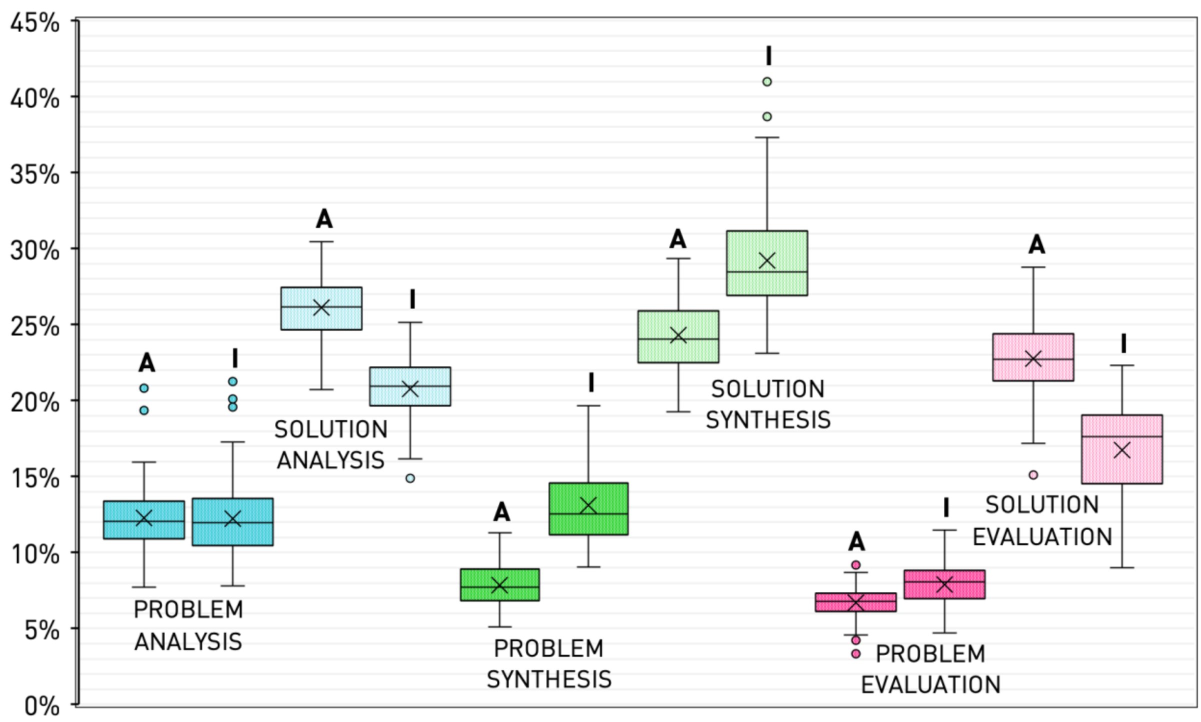

Figure 6.8 Box plot of proportions of ASE design operations within problem space and solution space, obtained from adaptive (A) and innovative (I) design simulations

The differences in the distributions of design operations are aligned with the characteristics of adaptive and innovative design summarised in Table 6.2, which have been used to set up the computational experiment studies. The response characterised by the higher proportions of both problem and solution synthesis in innovative design and higher proportions of solution analysis and evaluation in adaptive design, as well as differences in segments taken, deviations in the number of instances per design operation and the proportions visualised in Figure 6.8, serves as an initial verification of the computational simulation tool (the measures of outputs are in line with the expectations based on the values of the input parameters). However, further efforts of verifying and validating the simulation tool have been omitted, since the realisation of a final computational tool is outside the scope of this thesis. The presented research instead aims at providing a theoretical and mathematical foundation for simulating team design activity.

The following subsections report on the analysis of results that could not have been simply predicted before the simulation runs – probabilities and proportions of sequences of design operations, and how they change throughout the conceptual design of innovative and adaptive technical systems development.

6.3.2. Simulated sequences of design operations

The probabilities of moves from one design operation to another have again been interpreted as probability (Markov) matrices. For each simulation run, the total number of moves between pairs of design operations has been counted and entered into the corresponding cells of the matrix. The rows of the matrix were normalised to calculate the probabilities. Each of the resulting matrices represents the probability matrix for that particular simulation run. In order to summarise the data, the probability matrices have been averaged per sets of adaptive and innovative design simulation runs. The resulting average probability matrices are shown in Table 6.7. The cells of the matrices are here again coloured (heat map) in order to facilitate identification of moves between design operations that are most likely to appear.

During adaptive design, the most probable design operation to come after problem analysis was solution synthesis (32.0% probability), after problem synthesis, it was problem analysis (35.1%), and after problem evaluation, it was also problem analysis (37.9%). Solution analysis was most likely to be followed by solution synthesis (35.2%), and solution synthesis and solution evaluation by solution analysis (48.3% and 31.5% respectively). As for the aggregated design operations, the most likely moves were as follows: analysis was most likely followed by synthesis (43.8%), synthesis by analysis (50.3%) and evaluation by analysis (43.0%)

Table 6.7 Averaged probabilities of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from adaptive and innovative design simulations

ASE design operations in problem and solution space

		→PA	→PS	→PE	→SA	→SS	→SE
Adaptive design simulation	PA→	0.140	0.260	0.180	0.060	0.320	0.040
	PS→	0.351	0.189	0.054	0.108	0.189	0.108
	PE→	0.379	0.069	0.034	0.241	0.207	0.069
	SA→	0.070	0.031	0.016	0.219	0.352	0.313
	SS→	0.033	0.033	0.000	0.483	0.175	0.275
	SE→	0.054	0.076	0.163	0.315	0.272	0.120
Innovative design simulation	PA→	0.092	0.305	0.202	0.019	0.366	0.015
	PS→	0.221	0.195	0.164	0.089	0.273	0.057
	PE→	0.309	0.183	0.029	0.206	0.211	0.063
	SA→	0.036	0.079	0.033	0.090	0.446	0.316
	SS→	0.042	0.041	0.023	0.360	0.321	0.212
	SE→	0.072	0.133	0.025	0.284	0.314	0.172

ASE design operations

		→A	→S	→E
Adaptive design simulation	A→	0.264	0.438	0.298
	S→	0.503	0.248	0.248
	E→	0.430	0.331	0.240
Innovative design simulation	A→	0.122	0.567	0.312
	S→	0.379	0.389	0.232
	E→	0.393	0.434	0.172

During innovative design, the most likely moves starting with each of the ASE design operations in problem and solution space were as follows: problem analysis and problem synthesis were most likely to be followed by solution synthesis (36.6% and 27.3% respectively), and problem evaluation by problem analysis (30.9%), solution analysis by solutions synthesis (44.6%), solution synthesis by solution analysis (36.0%), and solution evaluation by solution synthesis (31.4%). The most likely moves for each of the aggregated ASE design operations were as follows: analysis was most likely to be followed by synthesis (56.7%), synthesis by synthesis (38.9%) or analysis (37.9%), and evaluation by synthesis (43.4%) or analysis (39.3%).

Probability matrices of individual simulation runs can be multiplied with the corresponding proportions of design operations in order to calculate proportions of particular moves between two design operations for that particular simulation run. The resulting proportion matrices can then be averaged per sets of adaptive and innovative design simulation runs to summarise the data. Averaged proportion matrices, which summarise the conceptual design of adaptive and innovative technical systems development, are shown in Table 6.8.

Table 6.8 Averaged proportions of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from adaptive and innovative design simulations

ASE design operations in problem and solution space

Adaptive design simulation

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.015	0.029	0.020	0.007	0.035	0.004
PS→	0.029	0.015	0.004	0.009	0.015	0.009
PE→	0.024	0.004	0.002	0.015	0.013	0.004
SA→	0.020	0.009	0.004	0.061	0.099	0.088
SS→	0.009	0.009	0.000	0.127	0.046	0.072
SE→	0.011	0.015	0.033	0.064	0.055	0.024

ASE design operations

	→A	→S	→E
A→	0.103	0.171	0.116
S→	0.173	0.086	0.086
E→	0.114	0.088	0.064

Innovative design simulation

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.008	0.026	0.018	0.002	0.032	0.001
PS→	0.025	0.022	0.019	0.010	0.031	0.007
PE→	0.018	0.011	0.002	0.012	0.012	0.004
SA→	0.008	0.017	0.007	0.019	0.097	0.069
SS→	0.014	0.014	0.008	0.122	0.109	0.072
SE→	0.013	0.024	0.005	0.052	0.058	0.032

	→A	→S	→E
A→	0.037	0.172	0.095
S→	0.172	0.177	0.105
E→	0.095	0.105	0.042

To enable a qualitative comparison of the micro-scale design processes exhibited by teams engaged in adaptive and innovative design, the average proportion matrices have been mapped onto the state-transition model visualisation proposed in Figure 3.4. The resulting visualisation (Figure 6.9) reflects the average proportional distribution of sequences of design operations throughout the innovative and adaptive design simulations. Furthermore, the visualisation provides insight on what design operations are likely to follow once a problem or solution entity has been analysed, synthesised or evaluated. In this way, the traces of phenomena such as continuous evolution of problem and solution space, as well as problem-solution co-evolution can also be visualised. The overall thickness of the arrows entering the state nodes reflects the proportion of analysis, synthesis and evaluation during the activities.

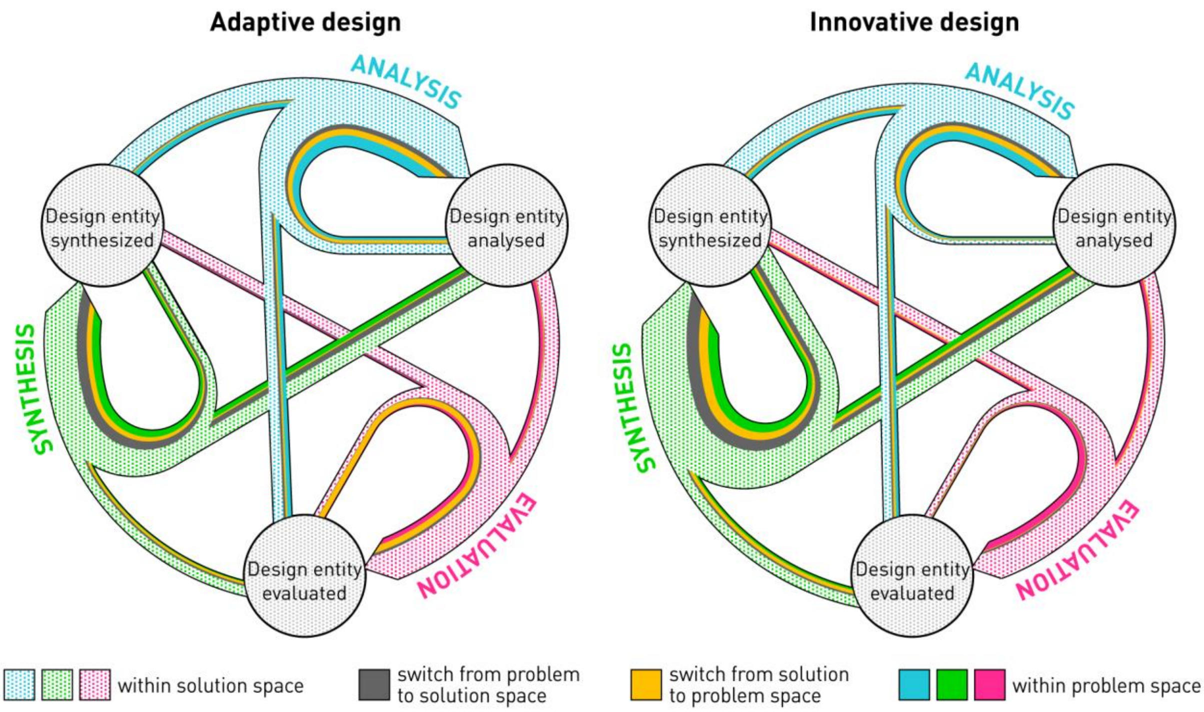

Figure 6.9 State-transition visualisation of average proportions of sequences of ASE design operations within and in-between problem and solution space during adaptive (left) and innovative (right) design simulations

Analogue to the protocol analysis study, further analysis can be conducted by taking into account sequences of three consecutive design operations, thus facilitating identification of patterns related to performing ASE design operations in the problem and the solution space. The sequences of three design operations were counted, normalised and summarised across simulation runs, thus providing average proportions of particular moves between three design operations (Table 6.9).

State-transition sequences during adaptive design

The averaged proportions of moves between ASE design operations during the adaptive conceptual design simulations (Figure 6.9 on the left, based on Table 6.8) exhibit some similarity in performing analysis, synthesis and evaluation within the problem and the solution space. The most frequent sequences of two design operations within both spaces were from analysis to synthesis and from synthesis to analysis. The moves between two analysis, two synthesis and two evaluation design operations were among the least present in both spaces. Nevertheless, the proportion of moves in problem and solution space differs largely in the case of the synthesis to evaluation sequence, which appeared primarily within the solution space.

Table 6.9 Averaged proportions of sequences of three consecutive design operations obtained from adaptive and innovative conceptual design simulations

Adaptive design

	→PA	→PS	→PE	→SA	→SS	→SE
PA→PA→	0.009	0.007	0.005	0.001	0.006	0.001
PA→PS→	0.011	0.003	0.004	0.002	0.004	0.002
PA→PE→	0.009	0.003	0.000	0.006	0.003	0.002
PA→SA→	0.001	0.000	0.000	0.001	0.002	0.002
PA→SS→	0.002	0.001	0.000	0.016	0.006	0.008
PA→SE→	0.001	0.000	0.001	0.002	0.001	0.002
PS→PA→	0.006	0.006	0.004	0.001	0.007	0.001
PS→PS→	0.003	0.001	0.001	0.001	0.002	0.001
PS→PE→	0.005	0.002	0.000	0.004	0.002	0.001
PS→SA→	0.000	0.000	0.000	0.002	0.002	0.002
PS→SS→	0.001	0.000	0.000	0.007	0.003	0.003
PS→SE→	0.001	0.001	0.001	0.003	0.003	0.002
PE→PA→	0.004	0.004	0.005	0.001	0.006	0.002
PE→PS→	0.003	0.001	0.002	0.001	0.001	0.001
PE→PE→	0.000	0.000	0.000	0.001	0.000	0.000
PE→SA→	0.001	0.001	0.001	0.003	0.005	0.009
PE→SS→	0.000	0.000	0.000	0.004	0.002	0.003
PE→SE→	0.000	0.001	0.000	0.002	0.001	0.001
SA→PA→	0.003	0.004	0.003	0.001	0.005	0.001
SA→PS→	0.004	0.002	0.003	0.001	0.003	0.002
SA→PE→	0.003	0.001	0.000	0.002	0.001	0.001
SA→SA→	0.004	0.003	0.002	0.010	0.015	0.015
SA→SS→	0.005	0.003	0.000	0.038	0.017	0.022
SA→SE→	0.006	0.006	0.008	0.029	0.021	0.021
SS→PA→	0.002	0.003	0.002	0.001	0.004	0.000
SS→PS→	0.002	0.001	0.001	0.000	0.002	0.001
SS→PE→	0.000	0.000	0.000	0.001	0.000	0.000
SS→SA→	0.006	0.007	0.003	0.021	0.038	0.032
SS→SS→	0.002	0.002	0.000	0.021	0.011	0.012
SS→SE→	0.004	0.004	0.005	0.021	0.017	0.014
SE→PA→	0.002	0.002	0.004	0.001	0.005	0.001
SE→PS→	0.004	0.001	0.003	0.001	0.002	0.003
SE→PE→	0.006	0.002	0.001	0.007	0.003	0.001
SE→SA→	0.004	0.003	0.002	0.012	0.023	0.029
SE→SS→	0.003	0.001	0.000	0.023	0.010	0.017
SE→SE→	0.003	0.003	0.005	0.016	0.012	0.015

Innovative design

	→PA	→PS	→PE	→SA	→SS	→SE
PA→PA→	0.004	0.006	0.005	0.000	0.004	0.000
PA→PS→	0.012	0.007	0.008	0.002	0.006	0.002
PA→PE→	0.011	0.006	0.001	0.005	0.002	0.003
PA→SA→	0.000	0.000	0.000	0.000	0.001	0.001
PA→SS→	0.002	0.002	0.001	0.013	0.009	0.007
PA→SE→	0.000	0.000	0.000	0.000	0.000	0.000
PS→PA→	0.007	0.012	0.009	0.001	0.011	0.000
PS→PS→	0.007	0.005	0.004	0.001	0.005	0.001
PS→PE→	0.010	0.006	0.001	0.005	0.003	0.003
PS→SA→	0.000	0.001	0.000	0.001	0.003	0.002
PS→SS→	0.002	0.002	0.000	0.009	0.008	0.005
PS→SE→	0.001	0.001	0.000	0.002	0.002	0.001
PE→PA→	0.005	0.008	0.007	0.001	0.007	0.000
PE→PS→	0.005	0.003	0.003	0.001	0.003	0.001
PE→PE→	0.001	0.000	0.000	0.001	0.000	0.000
PE→SA→	0.001	0.001	0.001	0.002	0.006	0.005
PE→SS→	0.000	0.000	0.000	0.003	0.002	0.002
PE→SE→	0.000	0.002	0.000	0.003	0.002	0.001
SA→PA→	0.001	0.003	0.002	0.000	0.003	0.000
SA→PS→	0.004	0.002	0.003	0.001	0.004	0.001
SA→PE→	0.003	0.002	0.000	0.002	0.001	0.001
SA→SA→	0.001	0.002	0.001	0.004	0.011	0.008
SA→SS→	0.005	0.004	0.002	0.033	0.024	0.019
SA→SE→	0.003	0.009	0.003	0.017	0.018	0.010
SS→PA→	0.002	0.005	0.003	0.000	0.005	0.000
SS→PS→	0.004	0.003	0.003	0.001	0.004	0.001
SS→PE→	0.001	0.001	0.000	0.001	0.001	0.001
SS→SA→	0.005	0.008	0.005	0.013	0.048	0.029
SS→SS→	0.004	0.005	0.001	0.030	0.026	0.017
SS→SE→	0.004	0.010	0.002	0.018	0.021	0.009
SE→PA→	0.001	0.002	0.002	0.000	0.004	0.000
SE→PS→	0.007	0.004	0.005	0.001	0.005	0.002
SE→PE→	0.003	0.001	0.000	0.002	0.001	0.001
SE→SA→	0.002	0.003	0.002	0.006	0.019	0.015
SE→SS→	0.003	0.003	0.001	0.019	0.014	0.012
SE→SE→	0.001	0.003	0.002	0.008	0.008	0.005

Examination of three subsequent design operations (Table 6.9) reveals the most frequent sequences within the problem space: analysis - synthesis - analysis (on average 1.1% of all sequences) as well as analysis - analysis - analysis and analysis - evaluation - analysis (both 0.9%); and within the solution space: analysis - synthesis - analysis and synthesis - analysis - synthesis (both 3.8%), followed by synthesis - analysis - evaluation (3.2%).

Regarding the moves from one space to another, the simulated teams would switch from solution to problem space mainly to perform problem analysis (on average 4.0% of all moves per team), followed by problem evaluation (3.7%) and problem synthesis (3.3%). On average, the most frequent moves from solution to problem space were from solution evaluation to problem evaluation (3.3%) followed by the moves from solution analysis to problem analysis (2.0%) and solution evaluation to problem synthesis (1.5%). As for the opposite direction, when switching to the solution space, teams did it primarily to synthesise solutions (on average 6.3% of all moves per team), and less frequently to analyse (3.1%) and evaluate (1.7%) solutions. However, while problem analysis and synthesis were most frequently followed by solution synthesis when space was switched, problem evaluation was most frequently followed by solution analysis.

The probabilities of moves in adaptive conceptual design simulations (Table 6.7) show that once the teams switched from problem to solution space, they were very likely to stay there for the next few transitions. However, the same practice in the opposite direction was not emphasised. Adding up of proportions of design operation moves presented in Table 6.8 shows that on average 63.6% of the moves took place within the solution space, 14.2% within the problem space, and 22.1% in-between the spaces. The most frequent sequence of three design operations which led to switching from problem to solution space was: problem synthesis - problem analysis - solution synthesis (on average 0.7% of all sequences). The other way around it was: solution analysis - solution evaluation - problem evaluation (0.8%). Please consult Table 6.9 for a detailed proportional overview of sequences of three design operations.

State-transition sequences during innovative design

Some of the observed proportions of sequences of ASE design operations during innovative conceptual design are similar, while others are fairly different in comparison to the results reported for adaptive design (Figure 6.9 on the right, based on Table 6.8). For example, the proportions of switching spaces are similar to the adaptive design: when the simulated teams shifted from problem to solution space during innovative design, they frequently performed also several next transitions within the solution space. On average 63.0% of the design operation moves took place within the solution space and only 14.9% within the problem space, with 22.1% of moves in-between the problem and the solution space.

The most frequent sequences of design operation within both the problem and the solution space were slightly different when compared to the adaptive design. In the problem space, the most frequent sequences were from analysis to synthesis (2.6%), from synthesis to analysis (2.5%) and from synthesis to synthesis (2.2%). The innovative design exhibited higher frequencies of moves from problem synthesis to problem evaluation (1.9%). In the solution space, the most frequent sequence was synthesis to analysis (12.2%), followed by synthesis to synthesis (10.9%) and analysis to synthesis (9.7%). The frequency of the solution analysis - solution analysis moves is considerably smaller when compared to adaptive design. Nevertheless, low proportions of moves from evaluation to evaluation have been identified within both spaces (as was the case with adaptive design).

Further examination reveals that the most frequent sequences of three design operations (Table 6.9) within the solution space were synthesis – analysis - synthesis (on average 4.8% of all sequences), analysis - synthesis - analysis (3.3%), synthesis - synthesis - analysis (3.0%), and synthesis - analysis – evaluation (2.9%). The most frequent sequences of three design operations within the problem space were analysis - synthesis – analysis and synthesis - analysis - synthesis (both on average 1.2% of all sequences), as well as analysis - evaluation - analysis (1.1%) and synthesis - evaluation - analysis (1.0%);

Switching spaces was somewhat different in comparison to the adaptive design. The simulated teams most frequently switched from solution to problem space in order to synthesise new problems (on average 5.5% of all moves per team). The other way around, teams frequently switched from problem space to solution space to perform solution synthesis (7.5%). For example, both problem analysis and problem synthesis were most frequently followed by solution synthesis once space was switched.

The most frequent sequence of three design operations which led to switching from problem to solution space was: problem synthesis - problem analysis - solution synthesis (1.1% of all sequences). The most frequent sequences from solution to problem space were solution synthesis - solution evaluation - problem synthesis (1.1%) and solution analysis - solution evaluation - problem synthesis (0.9%, see Table 6.9 for a detailed overview of sequences).

6.3.3. Simulated change in proportions throughout conceptual design

Moving average analysis of the simulated protocol strings is impractical, due to a relatively large number of teams investigated (simulation runs) when compared to the protocol analysis study. Namely, moving average is more suitable for the analysis of a single set of data points rather than multiple protocol strings, primarily because the simulations resulted in protocol strings of different lengths (different number of segments in the simulated processes). As an alternative to the moving average analysis, the protocol strings of each individual simulation have been divided into ten fractions of an equal number of protocol instances – from here on called deciles [55], [207]. Each decile has then been analysed in terms of proportions of design operations and their sequences as described in the previous subsections. Finally, the results have been averaged across all simulation runs for adaptive and innovative design, thus providing an overview of an average change in proportions throughout the two cases of conceptual design simulations.

Three types of analyses have been performed using deciles – analysis of change in proportions of ASE design operations within the problem and the solution space (Figure 6.10); analysis of change in proportions of sequences of ASE (Figure 6.11); and analysis of change in proportions of sequences of problem- and solution-related design operations (Figure 6.12).

The change in average proportions of design operations is to a large degree in line with the setup of simulation inputs – both adaptive and innovative design processes exhibit higher proportions of problem analysis at the beginning of conceptual design, peaks of solution synthesis in the middle and a continuous increase in proportions of solution evaluation as conceptual design progresses. Nevertheless, the changes in proportions in-between deciles are more apparent during adaptive design.

Within the averaged adaptive design simulation (Figure 6.10, top), the proportions of problem synthesis and analysis drop significantly towards the middle of the process and then again slightly increase towards the end, together with problem evaluation. Solution analysis is present throughout the conceptual design, with the highest proportions at the beginning and the very end. The process exhibits a low average proportion of solution evaluation at the start; however, it increases significantly in the second half of the simulated conceptual design stage. The simulated proportions of ASE sequences during adaptive design complement the above-described patterns (Figure 6.11, top). For example, the alternation between analysis and synthesis is the highest in the first three deciles. From that point on, proportions of moves from analysis and synthesis towards evaluation, as well as the proportion of cycles of evaluation increase. In the second half, the process exhibits frequent moves from analysis to evaluation and from evaluation back to analysis, and a significant drop of moves towards synthesis. Finally, aggregating the change in proportion using problem- and solution-related design operations (Figure 6.12, top) reveals high proportions of discussing problems at the beginning and then again slight increase towards the end of conceptual design. This trend is somewhat followed by the proportions of moves in-between the problem and the solution space; however, to a significantly lesser degree.

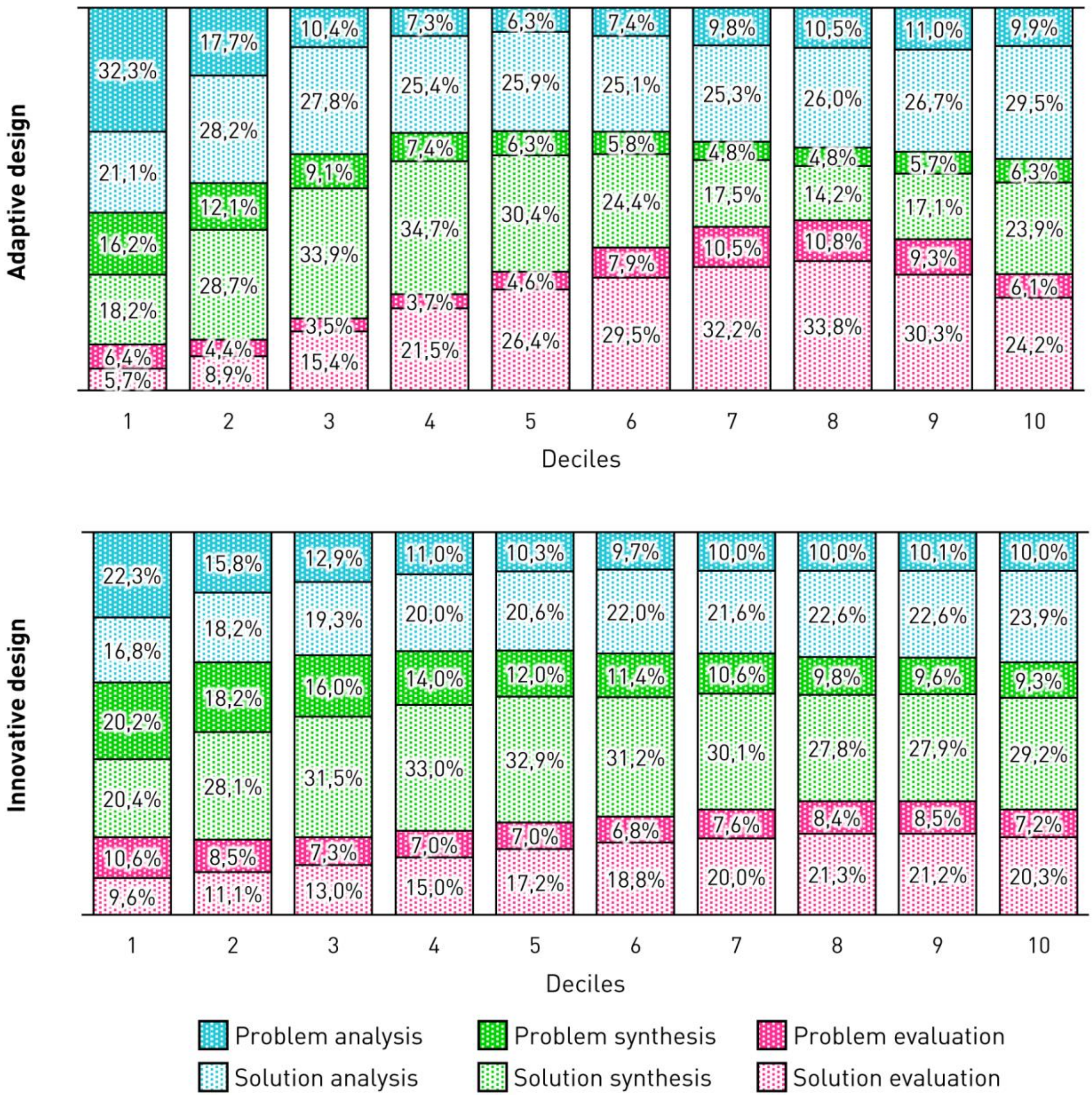

Figure 6.10 Average proportions of ASE design operations within problem and solution space across deciles of adaptive (top) and innovative (bottom) design simulations

The changes in proportions of design operations are less evident within the averaged innovative design simulation (Figure 6.10, bottom). Nevertheless, the innovative design process exhibits a noticeable peak of problem synthesis at the beginning, and solution synthesis in the middle of conceptual design simulation. The average proportion of analysis changes only slightly throughout the process. However, the ratio of problem analysis and solution analysis decreases towards the end. Overall, the average proportion of evaluation increases continuously. Nevertheless, the highest average proportion of problem analysis is in the first decile, whereas the highest average proportion of solution evaluation is in the last four deciles.

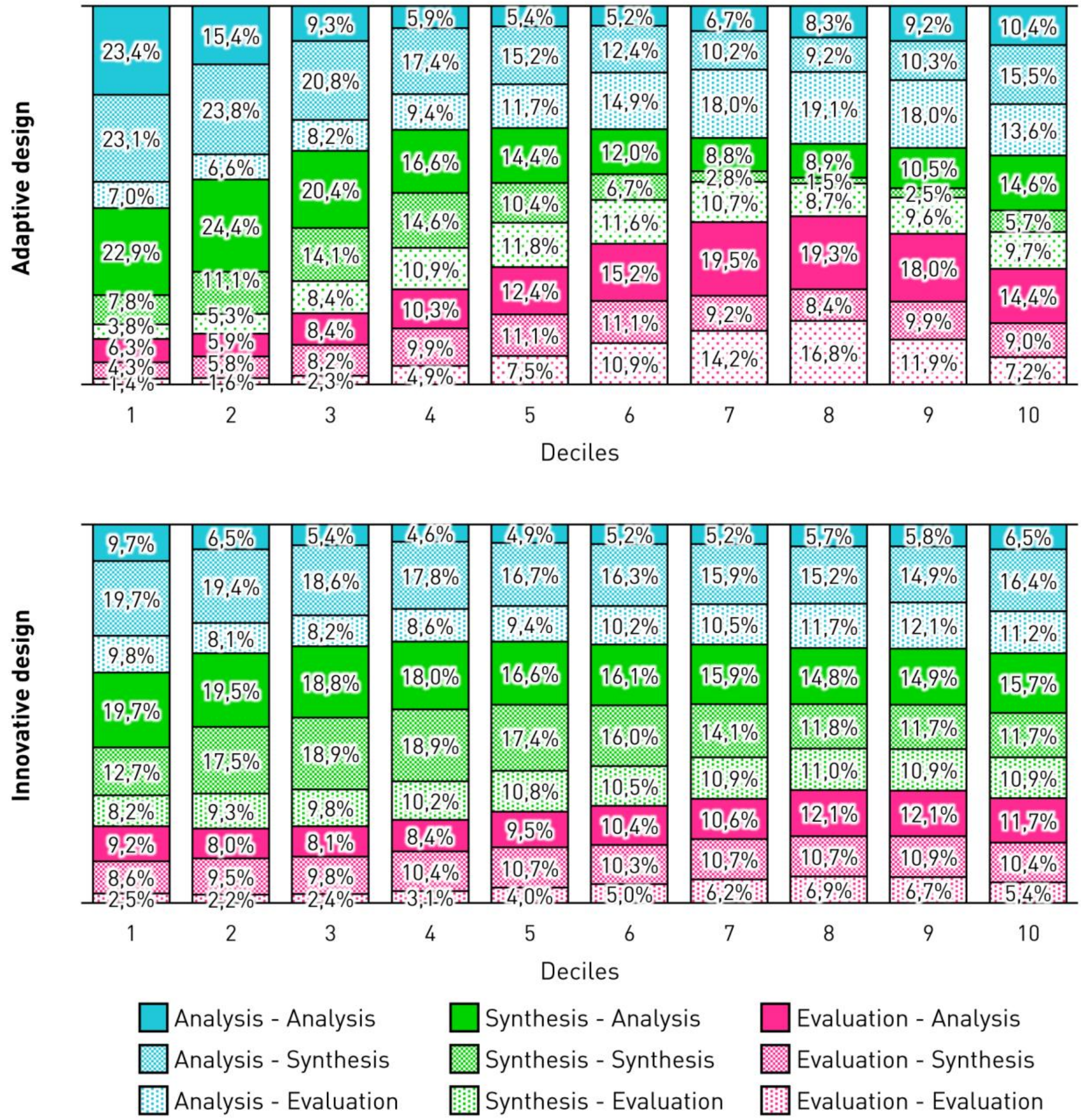

Figure 6.11 Average proportions of sequences of ASE design operations across deciles of adaptive (top) and innovative (bottom) design simulations

The alternation of analysis and synthesis sequences dominates the complete averaged innovative design process, particularly at the beginning (Figure 6.11, bottom). As for sequences of a single design operation, analysis cycles are present at the beginning, synthesis cycles toward the middle, and evaluation cycles towards the end of the innovative design process.

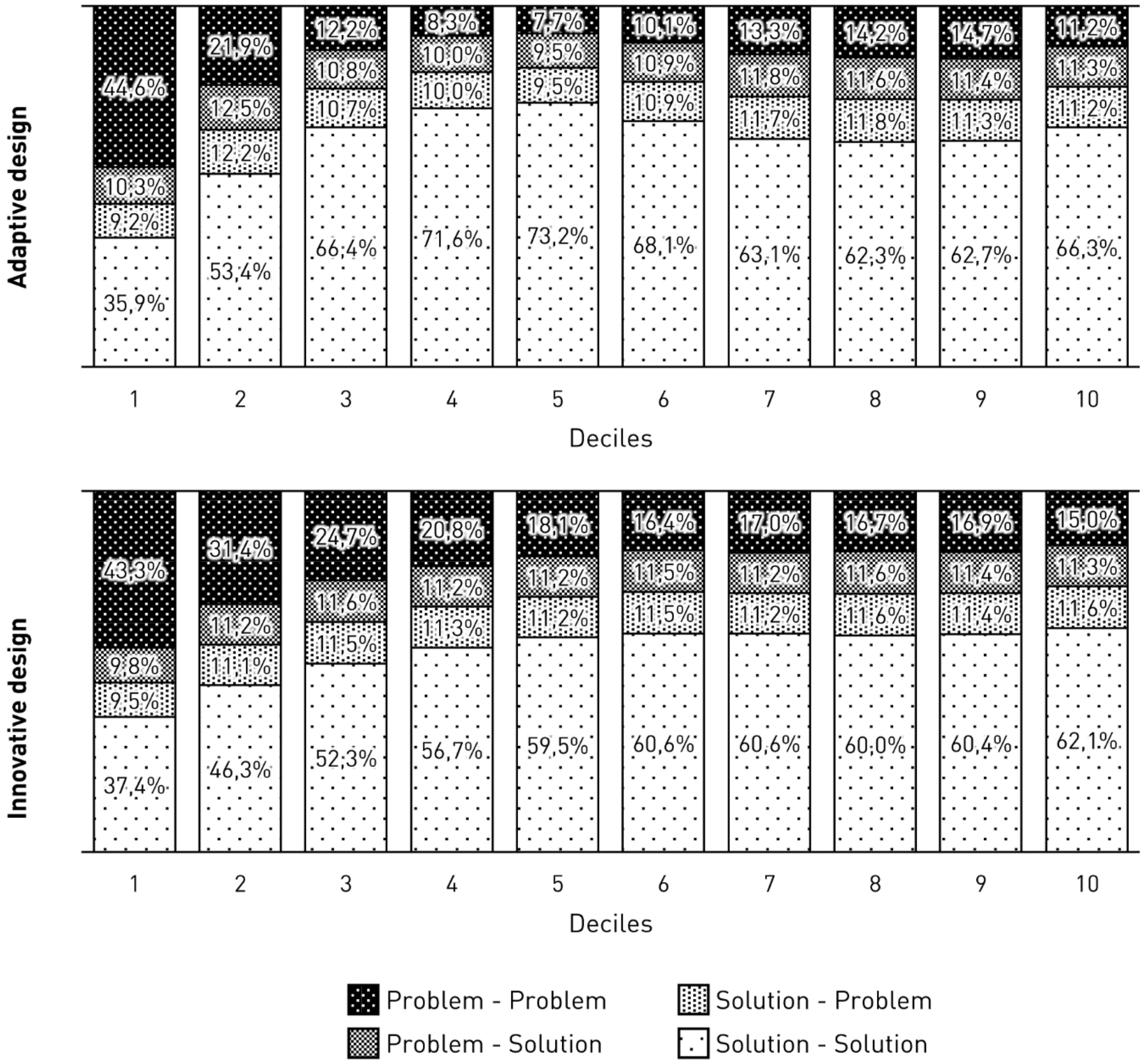

Figure 6.12 Average proportions of sequences of problem- and solution-related design operations across deciles of adaptive (top) and innovative (bottom) design simulations

Unlike during the adaptive design process, the average proportions of problem-related design operations decrease continuously until the end of the process (Figure 6.12, bottom). Interestingly, the average proportions of moves between the problem and the solution space do not change significantly with the progress of innovative design process. This means that sequences of several consecutive design operations within the problem space are more likely in the first deciles, whereas later in the process teams quickly switch back to the solution space. A similar claim can also be made for the adaptive design process.

7. DISCUSSION AND VALIDATION

The seventh chapter discusses the results and compares them to the insights available in the design research literature. The primary aim of this discussion and validation is to address the research questions using the findings obtained from the protocol analysis and computational studies. The extent to which the research questions have been clarified and the compatibility with the existing research is thus used to validate the developed theoretical framework, the theoretical and mathematical models, and the associated visualisations.

As the final research step, the state-transition approach to modelling team design activity, which has been framed in the form of a theoretical model (Chapter 3), formalised in the form of a mathematical model (Chapter 5), and experimentally tested by means of protocol analysis (Chapter 4) and computational studies (Chapter 6), is discussed and validated in this chapter. The discussion has been structured in five sections, each of which addresses one of the research questions raised at the end of the research background (Chapter 2).

First, a reflection on the models and their ability to capture ASE and their interaction in team design activities (RQ1) is discussed in Section 7.1. Following is the discussion and validation of general state-transition patterns found in team conceptual design activity (RQ2) in Section 7.2. The discussion then focuses on patterns specific to the team ideation and concept review activities (RQ3) in Section 7.3 and the overall trends identified for the progress of the conceptual design stage (RQ4) in Section 7.4. Finally, adaptive and innovative conceptual design of technical systems (RQ5) are discussed in Section 7.5.

7.1. Reflection on the state-transition model

The first point of the discussion addresses the research question RQ1, which prompted the framing of ASE as information-processing mechanisms performed by designers to manipulate the design information content in the problem and the solution space. This research question has initially been addressed within the theoretical framework chapter (Chapter 3), where the state-transition model and the accompanying variables, measures and visualisations have been proposed as a response. Following is a brief reflection on the utility of the model, based on the insights obtained from the protocol analysis and computational studies.

The benefit of adapting the definitions of ASE design operations built into the theoretical state-transition model manifests mainly in the proportions of solution analysis, problem synthesis and problem evaluation design operations. Firstly, the literature review revealed that analysis is often conceptualised only as a problem-clarification step in the design process (e.g. [75], [172], [210], [221]). However, the observed high proportions of solution analysis design operation (Subsection 4.3.1) reveal that teams spend a considerable portion of conceptual design activity increasing the understanding of design solutions. The theoretical model, therefore, exhibits the critical role of analysis as a design operation performed in both the problem and the solution space. It can be argued that both problem and solution analysis should be traced as independent fine-grain acts of designing in the conceptual design process, where the individual and shared understanding are increased by means of questioning and clarification, rather than being incorporated as part of evaluation (see, e.g. [218], [221]).

Secondly, the reviewed fine-grain models of designing articulate mainly the synthesis of new solution entities during the design activity (e.g. [54], [211]). Yet, the observed high proportions of problem synthesis design operation (Subsection 4.3.1) indicate that new problem entities also appear repeatedly throughout the team conceptual design activity. For example, ideation activities have shown highly probable cycles of problem synthesis design operations. Hence, by capturing the synthesis of design entities in both the problem and the solution space, the proposed theoretical framework complements the existing descriptive research efforts.

Finally, although neglected within the reviewed models of design activity, problem evaluation accounted on average for about 6% of all design operations during ideation, and 2% during concept review activity in the protocol analysis study (Subsection 4.3.1). In the computational study, problem evaluation exhibited average proportions of about 7% in adaptive design simulation and about 8% in innovative design simulations (Subsection 6.3.1). While these are relatively small proportions, they show that teams evaluate not only the proposed solutions but also the design entities within the problem space (e.g. requirement prioritisation and constraint assessment).

The theoretical model's ability to capture sequences of any pair of observable design operations (including the repetitive cycles of a single design operation) has resulted in representations of the team conceptual design activity which could not be replicated by other descriptive models of designing. Particularly, many of the observed patterns during ideation and concept review activity (e.g. alternation of analysis and synthesis, and the repetitive cycles of synthesis or analysis) cannot be directly and sequentially mapped on the reviewed models of design. For example, the FBS framework [207] does not favour (nor is it intended for) comprehensive investigation of subsequent instances of "transformative processes" between the FBS design issues. Namely, when deducting the transformative processes from strings of design issues codes, there exists no sequence of three FBS design issues that would reflect the analysis-synthesis, analysis-analysis or synthesis-synthesis transitions. In fact, the closest that synthesis can follow analysis in an uninterrupted sequence of FBS transformation processes related to a single entity is when evaluation appears in-between them (analysis-evaluation-synthesis sequence). And while such sequence of transitions might be the case at a cognitive design level or for individual designing, the reported study has shown that there are many observable episodes of analysis-synthesis moves appearing during team ideation and concept review. The same can be argued for synthesis-synthesis sequences occurring during ideation, and analysis-analysis and synthesis-evaluation sequences occurring during concept review.

Moreover, not all of the observed ASE patterns can be identically mapped onto the model of thinking in design teams by Stempfle and Badke-Schaub [54]. In their two-process model, new solutions must be followed by analysis or evaluation, and analysis must be followed by evaluation. Such constraints within the model prevent mapping of the aforementioned cycles. Again, this might be appropriate for modelling the thinking processes during the design process, but it does not reflect the nature of teams' observable design operations, which have a direct effect on the state of the product being designed and the state of the design process. The IMoD [218] by Srinivasan and Chakrabarti is more flexible in terms of design operation sequences and provides a more detailed insight into design synthesis by dividing it into generation and modification. However, IMoD does not distinguish analysis from evaluation, although analysis has here been portrayed as an important and often used design operation.

The probabilities of sequences of ASE design operations mapped onto the state-transition visualisation reveal that, although the analysis-synthesis-evaluation sequence does appear during both ideation and concept review activities, as well as in both innovative and adaptive design projects, the often-disputed model by Asimow [176] does not reflect the nature of conceptual design activity when using a fine-grain observational approach. The state-transition model has revealed that the analysis-synthesis-evaluation and synthesis-analysis-evaluation sequences are merely two of many appearing in the team conceptual design activity.

7.2. Team conceptual design activity

The second research question RQ2 concerns the patterns of ASE altering inside and in-between the problem space and the solution space, which can be observed during team conceptual design activities. Results of the various types of analyses reported in the protocol analysis study (Chapter 4) have been combined to address the question and discuss the alignment of new findings with the state-of-the-art insights available in the literature.

Although the proportions of segments related to discussions of the problem versus the solution space alter across the four observed teams (problem-solution focus of teams can vary as shown by Jiang et al. [55]), there exist similarities in proportions of sequences of executing ASE design operations within the two spaces. This similarity can primarily be explored during ideation, where, according to Table 4.4, teams spent significantly more protocol segments discussing the problem space. Qualitatively, the average order of most likely moves between ASE design operations (Table 4.7) is consistent when considering sequences within the problem and sequences within the solution space. During ideation, synthesis is in both spaces most likely to be followed by analysis and least likely by evaluation. During concept review, in both of the spaces synthesis is most likely to be followed by analysis and least likely by another synthesis design operation. Additionally, the most likely design operation to follow analysis during ideation was synthesis, and the least likely was analysis. On the other hand, the most likely move from evaluation during concept review was towards analysis, again regardless of the problem or solution space. These results can be related to the “find and modify” patterns of ideation, which Sarkar and Chakrabarti [225], [240] identified in both the problem and the solution space.

By analysing the sequential strings of coded segments for each of the observed teams, and the corresponding probabilities and proportions of moves between design operations, it is possible to examine the fine-grain patterns in teams’ design processes. Figures 7.1, 7.2 and 7.3 utilise the state-transition model visualisation to illustrate three common patterns of ASE design operation sequences obtained for both the ideation and the concept review activity. These patterns are conceptualised as templates on which sequences of several design operations can be mapped to indicate common micro-scale building blocks of the team conceptual design process. The patterns were initially identified within the strings of protocol codes, as sequences of coded segments which are articulated due to their repetition. The identified patterns have then been further investigated by mapping the observed probabilities of moves between design operations reported in Table 4.7 and proportions of these particular sequences which have been presented in Tables 4.10 and 4.11.

The first pattern which is present in both activities (Figure 7.1) comprises the reciprocating cycles of solution synthesis frequently intercepted by solution analysis. Moves in-between solution synthesis and analysis have been shown as the most probable during both activities (Table 4.7). Moreover, adding up the proportions of state transitions reveals that 57.1% of sequences of two

(Table 4.10), and 42.3% of sequences of three (Table 4.11) solution-related design operations during ideation can be mapped onto this pattern. As for concept review, the pattern includes 38.4% of sequences of two and 22.1% of three solution-related design operations. The first pattern can also be discerned in data simulated as part of the computational study (Chapter 6). It accounts on average for 42.8% sequences of two (Table 6.8) and 23.5% sequences of three solution-related design operations (Table 6.9) during adaptive design. The percentages of innovative design simulations covered by the first pattern are even higher: 52.1% of sequences of two and 34.9% of sequences of three solution-related design operations.

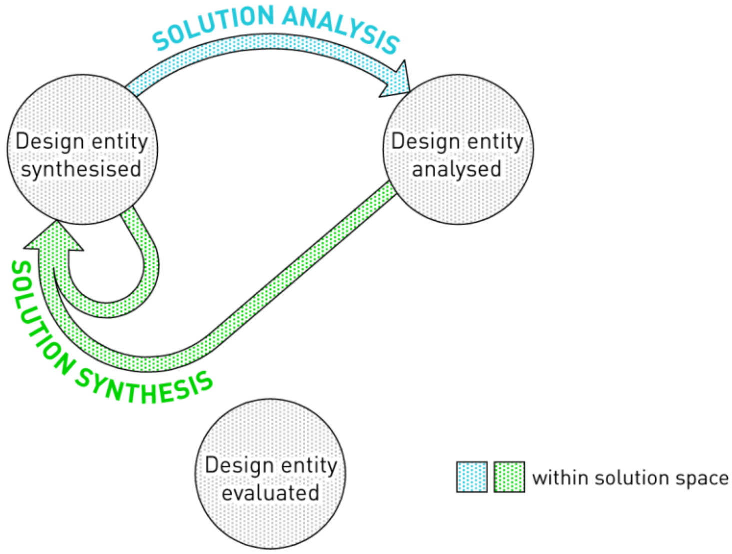

Figure 7.1 Cycles of solution synthesis and analysis

The cycles forming the first identified pattern have already been given attention in the literature. For example, Smith and Tjandra [277] interpreted analysis-synthesis cycles as iteration in design activity. They state that the iteration intensifies as conceptual design stage progresses. A similar interpretation has been provided by Sung and Kelley [204], who described the phenomenon as a bi-directional iteration of designing solutions and predicting possible consequences of the solution ideas. Cascini et al. [212] described the interplay of analysis and synthesis when moving from needs identification and requirements definition towards conceptual design stage. Furthermore, Sauder and Jin [56] have observed that questioning and clarification of design solutions (solution analysis) stimulates generative thinking processes which in return trigger generative (solution synthesis) design operations. Similarly, Cardoso et al. [203] interpreted questions as drivers of discourse in design team ideation activity. According to these studies, the analysis of the shared design space appears to be an important driver of stimulation responsible for the generative (synthesis) processes. Finally, the dominance of solution synthesis within the cycle can be characterised as a decoupled ideation [46], where solution ideas are appearing without the need of switching to problem space and triggering the co-evolution episodes.

The presented protocol analysis data thus support the claim that the alternation of synthesis and analysis in both the problem and the solution space is typical for conceptual design activities [171], [217]. An excerpt of the experiment session transcripts from the protocol analysis study, which demonstrates the first pattern, is available in Table 7.1.

Table 7.1 An excerpt of team discussion demonstrating the reciprocating cycles of solution synthesis and analysis

Participant	Segment transcript	Code
P1	[discussing attachment to the balloon] *We have to minimise the mass.*	PS
P2	*We could use welding.*	SS
P2	*Or... Uhm. Glue, adhesive.*	SS
P3 P2	*Adhesive? I guess we can call it both (glue and adhesive).* *Yes.*	SA
P3	*We also have Velcro.*	SS
P2	*You can put up magnetic.*	SS
P2	[gesturing] *Magnetic touch. I'm not sure how, but...*	SA
P3	*So, I guess we expand them now?*	PROC
P3 P2	*I got one actually, like a...* [gesturing] *I think is metal, like a flexible...* *Yeah, the Gorillapod thing.*	SS
P3 P2	*Is that what it's called?* *Yes. It's TP, thermoplastic.*	SA
	...	
P1 P2	[discussing which problem should be addressed next] *I think that camera movement is most important.* *OK.*	PE
P2	*If we want to move the camera mount from the base, I can think of one which has two sets of drills, rotation axes.*	SS
P2 P1	[gesturing] *One in this direction, and the other one in this direction. I don't know if you understood what I wanted to say?* *Yes.*	SA
P1	*You could have it on a ball.*	SS
P2 P2	*Oh, and then manipulate the ball?* *Yes, like a gyroscope or something.*	SA
P2 P1	*Can you sketch it?* [laughs] *Not really.*	PROC
P3	*Maybe driven by gears to control the angle.*	SS
P1	*You could have it... It does not have to be absolute any angle, because you could have like* [gestures] *30 degrees – 30 degrees – 30 degrees.*	SS
P3 P1	*Oh, distinct angles. Not continuous.* *Yes, distinct angles.*	SA

The second pattern of design operations (Figure 7.2) identified within both activities includes sequences of solution synthesis, analysis and evaluation. This pattern builds on the first (divergent) pattern by incorporating solution evaluation as a converging operation. According to protocol analysis study data (Tables 4.10 and 4.11), the summed-up proportions of state transitions included within the pattern account for 86.8% sequences of two, and 76.5% sequences of three solution-related design operations during ideation. Likewise, the pattern comprises 70.4% sequences of two, and 51.1% sequences of three solution-related design operations during concept review activity.

In addition, the second pattern can reflect 76.5% of moves between two (Table 6.8) and 52.4% of moves between three consecutive solution-related design operations (Table 6.9) simulated for the adaptive conceptual design process, as well as 83.7% of moves between two, and 67.2% of moves between three consecutive solution-related design operations simulated for the innovative design process.

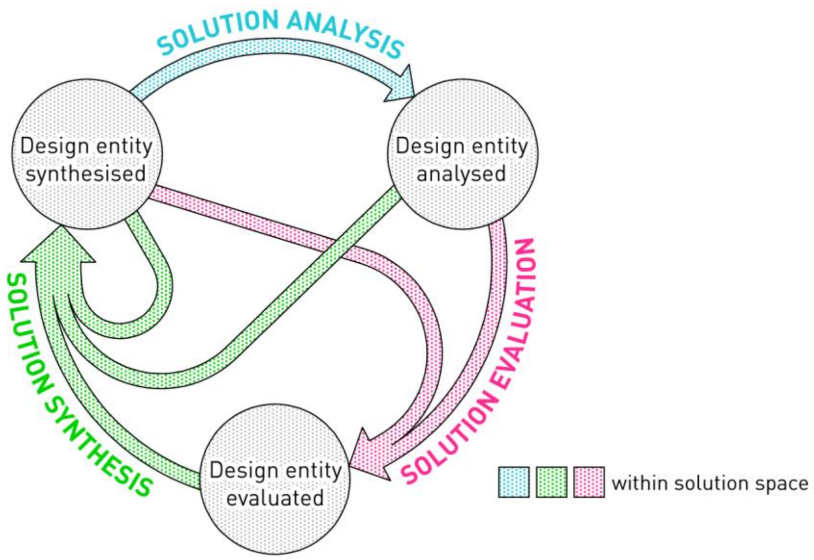

Figure 7.2 Sequences of solution synthesis, analysis and evaluation

The described sequences resemble the two types of thinking processes identified by Stempfle and Badke-Schaub [54], where synthesised solutions are either immediately evaluated (process 1), or first analysed and then evaluated (process 2). If the synthesised solution is discarded, a new idea will be sought [54]. A similar pattern can be described within the FBS framework, where a synthesised structure is first analysed to understand its behaviour, and then evaluated by comparing its behaviour to the expected behaviour [26]. An excerpt of the experiment session transcripts which demonstrates the second pattern is available in Table 7.2.

Table 7.2 An excerpt of team discussion demonstrating sequences of solution synthesis, analysis and evaluation

Participant	Segment transcript	Code
P1	[discussing alternatives to the universal screw camera attachment] *Duct tape – that is an idea.*	SS
P1	*I mean, it's not very usable, but…*	SE
P1	*We can use bands. Just bands.*	SS
P2	*Velcro?*	SS
P1	*Velcro. It can be sticked to the back of the camera.*	SA
P2	*Velcro works in space actually.*	
P3	*I think it works in space because there are no forces in vacuum.*	SE
P1	*But you could use it to connect… Like a pouch.*	SS
P3	*I'm not saying its a bad idea.*	SE
P3	*A bag? Bag / kangaroo pouch.* [laughs]	SS
P1	*The thing is, it's annoying if you have to screw your camera into something that is fixed, especially to a balloon…*	SE
P3	[interrupts and gestures] *A clip in.*	SS
P3	*Which can go* [points to written categories] *here?*	SA
P1	*Yes.*	

The third identified pattern (Figure 7.3) indicates co-evolution of the problem and the solution space by combining state transitions which result in switching in-between problems and solutions by means of synthesis design operation.

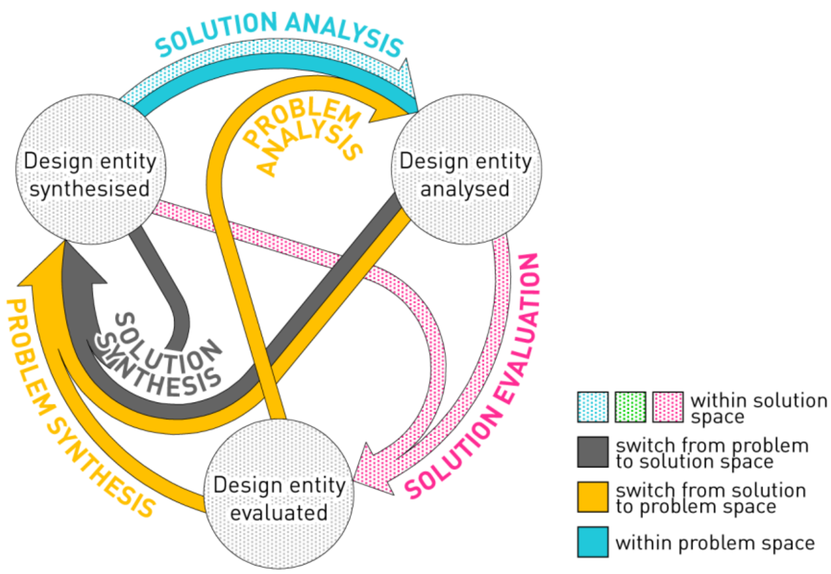

Figure 7.3 Synthesis as a means of switching in-between problem and solution space

State transitions which can be mapped onto the third pattern account for 56.6% of sequences of two (Table 4.10), and 30.8% of three consecutive design operations (Table 4.11) in-between the problem and the solution space during the observed ideation activity. If only sequences resulting in synthesis (as an indication of co-evolution) are considered, these percentages increase to 73.8% and 44.8%. As for concept review activity, 51.6% of sequences of any two, and 26.0% of any three consecutive design operations in-between the problem and the solution space can be mapped. Again, the percentages are higher (93.7% and 60.9%) if only transitions resulting in synthesis are considered.

In a similar manner, 38.5% of sequences of any two, and 22.5% of sequences of any three consecutive design operations simulated in-between the problem and solution space computational study of an adaptive process can be mapped onto the third common conceptual design pattern. These proportions increase to 77.1% for a sequence of two, and 25.2% for a sequence of three design operations, if only the switching of spaces that ends with a synthesis design operation is considered.

The results of innovative design simulations reveal that on average 52.9% of all sequences of two, and 26.5% of all sequences of three consecutive design operations that switch from problem to solution space or vice versa, can be mapped onto the third common pattern. If only sequences resulting in a synthesis of problem or solution entities are considered, the percentages increase to 80.0% and 27.1% respectively.

Once a synthesised solution entity is analysed or evaluated, a new problem is sometimes immediately discovered (synthesised) by the team members. As soon as the team develops a shared understanding of the new problem, they propose (synthesise) new solutions to the problem. In such co-evolution episode, the teams switch from solution to problem space and return to solution space. The new solution entity can again be further analysed and evaluated which can result in the identification of new problems. Such a pattern can be classified as a necessary part of refinement, a stereotype of progressive iteration as defined by Wynn and Eckert [170]. As the solution design goes through several levels of abstraction, each level can result in a new set of requirements [218], so the solution undergoes iterative refinement until it is evaluated as satisfying. The described iterative pattern also corresponds to what Cash and Štorga [46] define as integrated and iterative ideation since new solution ideas trigger new problems and vice versa. An excerpt of the experiment session transcripts which demonstrates the third pattern is available in Table 7.3.

Table 7.3 An excerpt of team discussion demonstrating synthesis as a means of switching in-between problem and solution space

Participant	Segment transcript	Code
P1	*I try to work out if we can get away with fewer motors than two.*	PS
P2	[points to previously discussed solution] *Exactly that's what I got over here.*	SE
P1	*Yeah. But I don't know, because if you wanted it pushing down and think 'Oh yes, I wanted that angle'. But it has only reached that far down and not...* [points to solution]	SA
P1	*Then you obviously can't use the exact rotation.*	SE
P1	*I think when you've got two degrees of freedom like that* [points to solution] *you need two... sort of... at least two motors.*	PS
P2	*What if you had a really tight spiral and it gradually taper it to a triangle?*	SS
P1	*Yes, so it's going through every conceivable thing just using one motor?*	SA
P2	*Yeah.*	
	...	
P1	*Could we just have like a... Plastic...* [starts sketching] *So it will be like that. And then we put it in. And then just have... It's like a plastic... Where you just push it, so it doesn't come out?*	SS
P2	*Yeah, like a clip.*	SA
P1	*Yeah, so instead of a locking mechanism. You can do it with one hand. Just push the latch and take it out, pull it out.*	
P1	*That would really simplify it.*	SE
P2	*I mean, my only concern with that is in case the latch came undone, because there's no spring holding it there. But in between somewhere of doing that [pointing to solution] and making sure it didn't come under...*	PS
P3	*What about a screw tightener thing... So that you have a notch inside...* [starts sketching] *You have your plate slit in, a little notch in the base thing. And you have a screw which just went in there.*	SS
P2	*So, it would be like a quarter inch screw and then just...* [gestures]	SA
P3	*Yeah.*	

7.3. Ideation and concept review

Following the identification of common patterns of ASE design operations within and in-between the problem and the solution space, the research question RQ3 prompted the recognition and analysis of patterns that differentiate ideation from concept review activity. The distribution of the coded design operations segments during the two types of experimentally studied conceptual design activities (Table 4.3 and Figure 4.4) and the corresponding t-tests (Tables 4.4 and 4.12) reveal that teams are likely to exhibit different proportions of ASE design operations when performing various types of conceptual design activities. The comparison of ideation and concept review has revealed that the proportion of all six coded design operations differs significantly for these two types of activities. Based on these findings, it is argued that the activity-specific probabilities of ASE design operations appearing within and in-between the problem and the solution space can be utilised to investigate and model the change in the state of the product being designed and change in the state of the design process as defined by Reymen et al. [199].

According to Table 4.4, teams exhibited significantly more problem-related discussion and solution synthesis during the ideation activity and significantly more solution analysis and evaluation during the concept review activity. Since ideation was the first collaborative activity of the teams, it was natural for them to seek a shared understanding of the problem [22], [58]. Moreover, the decrease of design operations in problem space (especially problem synthesis) can be related to the drop in new requirements appearing towards the end of the conceptual design stage, as identified by Chakrabarti et al. [278]. During the concept review activity, the teams were more familiar with the design problem (space). Such a trend is qualitatively aligned with the findings of Jiang et al. [55] and Gero et al. [207], which imply the decrease in the proportion of problem-related issues as the conceptual design progresses. Additionally, Gero and Jiang [206] conclude that the concept review activities seem to be more solution-focused than the designing (ideation) sessions.

Ideation is often characterised as a divergent activity, considering that the generative design operation (synthesis) dominates the convergent one (evaluation) [248]. The fact that synthesis was the most frequent design operation for all of the studied teams during ideation session favours such characterisation. Furthermore, the proportions of ASE design operations (Figure 4.4) correspond to the average proportions of the equivalent processes (within solution space) reported for the ideation activities in Gero et al. [207]. Their study suggests that these proportions are also affected by the type of ideation method used. For example, the protocol study of brainstorming sessions presented in Kan et al. (2011) shows a somewhat higher rate of synthesis design operation, mainly in the solution space. It can thus be argued that the application of design and creativity methods during the conceptual design activity will likely affect the fine-grain patterns of the design process.

On the other hand, the protocol analysis of the concept review activity has revealed significantly higher proportions of solution-related discussion, particularly manifested in higher proportions of solution analysis and evaluation design operations. The studies of conceptual design where the design brief instructed the proposal of a single concept solution (which had to converge) suggest that engineering design teams will most frequently perform solution analysis and solution evaluation design operations (solution analysis and problem clarification in Casakin and Badke-Schaub [279] and content analysis in Stempfle and Badke-Schaub [54], followed by solution evaluation). Moreover, despite the increase in solution-related discussion, the proportion of solution synthesis is significantly lower when compared to ideation, thus providing additional justification for describing concept review as mainly a convergent activity.

If the two activities are compared with the stereotypes of progressive iteration [170], a link can be found between ideation and exploration (divergence) stereotype, and between concept review and convergence stereotype. Wynn and Eckert [170] describe exploration as a concurrent and iterative initial development of the problem and the solution, where the ill-defined nature of design goals is emphasised. Such progressive iteration is reflected in the evolution and co-evolution of the problem space during ideation, as shown in Figure 7.4. Convergence is described as an iterative adjustment towards a satisfying goal, once the main form of the design has been determined at a certain level of definition [170]. During the concept review, the designers would select and synthesise the most promising concept and then iteratively refine different aspects of the final solution proposal.

The comparison of the two activities has revealed not only the different proportions of design operations (Table 4.4) but also the activity-specific sequences of ASE design operations. The activity-specific sequences represent the moves between two design operations whose probability changed significantly between the two types of activities (Table 4.12). The sequences with significantly higher probabilities during ideation and concept review activities have been illustrated as state transitions in Figure 7.4.

The significant changes in the probabilities of design operation sequences identified in Table 4.12 and Figure 6.4 again point out the divergent features of the ideation and convergent features of the concept review activity. As described, the divergent alternation of solution synthesis and analysis (Figure 7.1) accounts for almost 60% of solution-related discussions during ideation. However, as shown in Figure 6.4, the divergent features of ideation are also reflected in higher proportions of synthesis moves within the problem space, but also in-between the problem and the solution space. On the other hand, convergent cycles during the concept review activity are characterised by the sequences of analysis and evaluation design operations performed as part of developing and refining the final proposal of the conceptual solution (Figure 7.2). As shown in Figure 7.4, the probability of evaluating a synthesised solution is significantly higher during concept review.

Furthermore, the evaluated solutions are more likely to be repeatedly analysed. Here, the analysis design operation is essential for the better understanding of team members, and leads to progress in team design activities, whether it is used as clarification [222], [279], or questioning [203]. And while teams can, in general, be seen as collective information-processing entities, individuals within teams do not possess identical internal representations of problems and solutions [58]. Hence, achieving common ground (understanding), as highlighted by Hultén et al. [20], appears to be an essential ingredient of a team's creative processes during conceptual design activities.

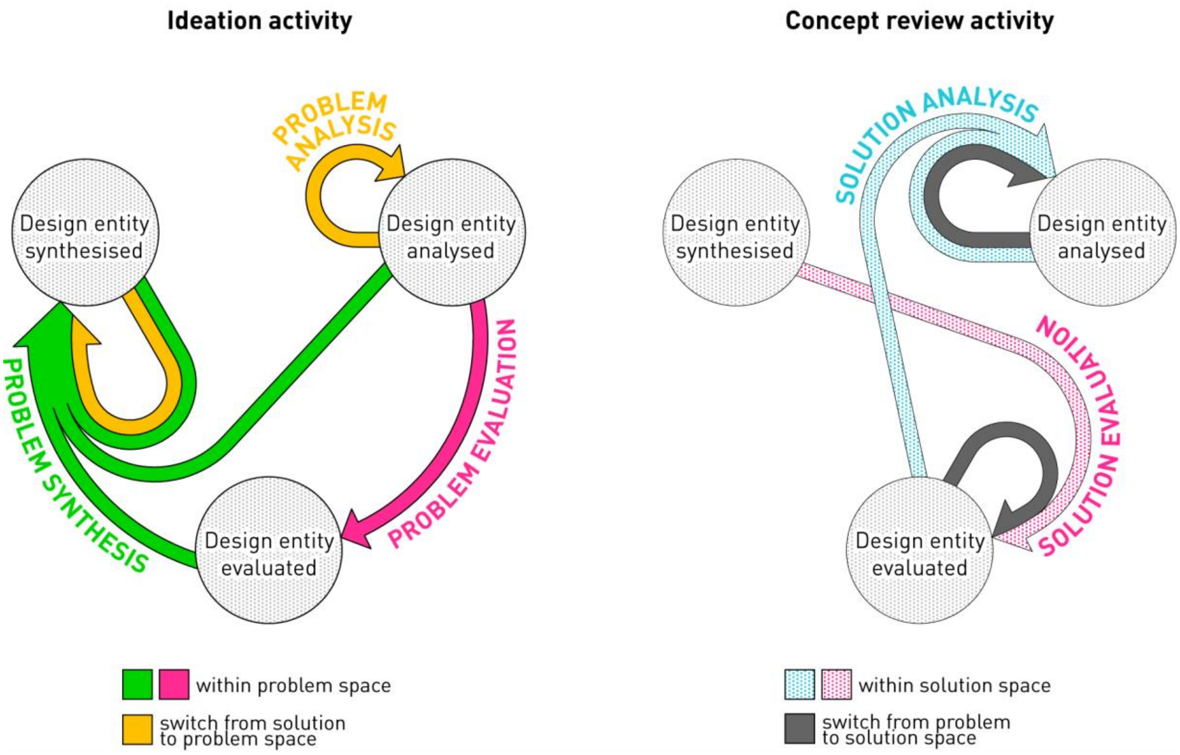

Figure 7.4 State transitions distinctive for ideation (left) and concept review activity (right)

Finally, the protocol analysis study provided an insight into teams' practices of using ASE design operations to switch from problem to solution space and vice-versa. An interesting finding is that moves from problem to solution space are performed mainly to synthesise new entities, while moves from solution to problem space appear either because a new problem was identified, or the focus is again set to the analysis of existing problem entities. Such patterns support the concept of problem-solution co-evolution as described in studies by Dorst and Cross [174] and Visser [173]. Therefore, the moves in-between the problem and the solution space which result in the synthesis of design entities can be characterised as identifiers of the likely co-evolution episodes.

Although studies have reported co-evolution during both ideation and concept review activities (e.g. [230]), there have been no clear insights on how the rate of co-evolution changes with the progress of conceptual design activity. Moreover, despite it is known that some of the previously mentioned emotional factors such as fatigue, effort, frustration, concentration, boredom, engagement and anxiety affect designers' behaviour, there remains a lot of research effort to study the effects of these phenomena on problem-solution co-evolution. While the effects of these factors could not here be directly observed, the protocol analysis shows moderately lower probabilities and frequencies of switching the space by performing synthesis design operation during the concept review activity, as opposed to ideation (moves from problem space to solution synthesis and from solution space to problem synthesis in Tables 4.7 and 4.10). Wiltschnig et al. [67] who analysed the phenomenon of co-evolution during several conceptual design meetings have identified that most of the co-evolution episodes imply new solution entities, rather than new problem entities. Similar insights can be drawn in this study, since the moves from problem space to solution synthesis, which are characteristic for such co-evolution episodes have been more frequent than moves from solution space to problem synthesis, during both of the activity types (as shown in Table 4.10 and Figure 4.8). Nevertheless, while this was indeed the most likely space-switching scenario, the probabilities of space-switching moves which imply synthesis of problem entities (moves from solution space to problem synthesis in Table 4.7) must not be neglected, particularly during concept review. Namely, the convergent design activities are focused on evaluating solutions rather than creating new ones. The evaluation design operation has been defined in a way that it can implicitly reveal decomposed problems [171]. Such problem decomposition is argued to be the main reason why problem synthesis design operations are likely to follow solution evaluation if space is switched. Also, Wiltschnig et al. [67] reported that requirement analysis (problem analysis) is expected to trigger most of the co-evolution episodes, resulting in solution attempts (solution synthesis). The presented study shows that problem analysis certainly plays a valuable role in co-evolution during both ideation and concept review, expressed in the high probability of solution synthesis following problem analysis (Table 4.7). However, it was found that problem synthesis is more likely to be preceded by solution analysis and evaluation rather than solution synthesis when co-evolution occurs (as seen in Table 4.7 and Figure 7.3).

7.4. Conceptual design progress

The change in patterns of ASE design operations throughout the conceptual design stage can be approached in two ways. First, the results of the protocol analysis study (Chapter 4) can be used to compare the difference in two team activities at different points of the conceptual design stage (ideation at the beginning and concept review towards the end of the overall conceptual design process). Such a comparison has been presented and discussed in the previous section. The other approach is to utilise the results from the simulation of conceptual design in adaptive and innovative design projects, reported as part of the computational study (Chapter 6). The commonalities found in the progress of the simulated processes of adaptive and innovative design can complement the protocol analysis study insights to develop an overall understanding of the relationship between the progress of conceptual design stage and patterns in performing design operations, thus addressing the research question RQ4.

Distinctive state transitions during ideation and concept review activities (Figure 7.4) revealed that the proportions and probabilities of moves within and towards the problem space are significantly higher in the earlier segments of the conceptual design stage. The decrease in problem-related segments has already been discussed as aligned with the findings of Jiang et al. [55] and Gero et al. [207]. In addition, a study of freshman and senior students' conceptual design process conducted by Altman et al. [280] revealed that the focus on problem scoping, that is problem definition and information gathering, has been most persisting from the beginning up until the end of the first half of the conceptual design stage. A similar pattern can be discerned in the protocols of Stempfle and Badke-Schaub [54], who analysed how teams execute a complete conceptual design task.

Nevertheless, since designers are "solution-led", rather than "problem-led", they tend to jump to solution ideas (or partial solutions) before they had fully formulated the problem [281]. For this reason, problem-related segments keep reappearing until the very end of the conceptual design stage. The constant development of problem space is best depicted by the average proportions of sequences of the problem- and solution-related design operations across the deciles of the conceptual design simulations (Figure 6.11) reported in Chapter 6.

The simulations of adaptive and innovative conceptual design (where problem-focus was one of the input parameters) indicated that, while the proportion of problem-related design operations decreases, the rate of switching between spaces does not change significantly throughout the conceptual design stage. What changes is that the simulated teams spent significantly fewer consecutive sequences within the problem space as the conceptual design stage progressed. It can be hypothesised that switching to the problem space later in the conceptual design process is related to discovering new problems or referring to the existing ones when evaluating concept solutions, rather than a deliberate exploration of the problem space. For example, Kan et al. [205] observed a decrease in the formulation and an increase in the reformulation of problem-related issues with the progress of a design session.

The results of the protocol analysis study indicate that when compared to the ideation activity, the concept review differs in higher proportions of solution analysis and evaluation, as well as higher probabilities of moves from solution analysis, synthesis and evaluation towards solution analysis, and from problem space to solution analysis and problem space to solution evaluation (Figure 4.8). The results of the computational study develop this insight further by depicting the increase in proportions of moves in-between analysis and evaluation (Figure 6.11) as adaptive and innovative conceptual design processes proceed.

Overall, it can be hypothesised that with the progress of the conceptual design stage, the initially higher proportions of synthesis cycles (divergent process) get gradually substituted by the alternation of analysis and evaluation design operations (convergent process). The divergent and convergent characteristics of the design process are thoroughly discussed in the previous section. Smith and Clarkson [282] explain that, while commitments made in the conceptual design stage are mainly functional, designers typically specify the realisation of the solution as they approach the latter stages of conceptual design. By developing the information on how the design works, not only is the problem reduced, but it is also easier for teams to determine "what can go wrong" [282] and conduct solution evaluation. Fricke [283] argues that, as design problem formulations get more precise, the increase of solution evaluation is crucial for successful concept development.

Interestingly, the alternation of analysis and synthesis is fairly persistent throughout the protocols obtained from both the protocol analysis and the computational studies of conceptual design. This insight again points out the critical role of analysis-synthesis cycle for concept generation, as proposed by some studies [56], [203], [204], [213], [277], and discussed in the previous section. It can be argued that fractions of the design process where sequences of analysis and synthesis design operations alternate (the first common pattern discussed in Section 7.1) appear consistently throughout team conceptual design activities.

The discussion on the relationship between the patterns of design operations and the progress of the conceptual design stage can be concluded with a hypothesis that the drop of uncertainty (whether high uncertainty in the case of innovative design or medium uncertainty in case of adaptive design [44], [188]) is proportional to the decrease in proportions of problem-related design operations, as well as inversely proportional to the increase of solution analysis and evaluation design operations. This hypothesis can be further investigated as part of future studies.

7.5. Innovative and adaptive design

The research question RQ5 is oriented at investigating the prevalent patterns of design operations which can be identified for different types of technical systems development. Here, in particular, the novelty aspect of a technical system has been reflected using the types of engineering design projects. The two compared novelty levels were adaptive and innovative design. More details on the computational analysis of design operation patterns within the adaptive and innovative conceptual design can be found in Chapter 6. The similarities between the two have already been analysed in the previous section, where the overall patterns that arise from conceptual design progress are discussed. This section focuses on the distinctive features of adaptive and innovative design processes simulated in Chapter 6 and demonstrates how these distinctive features can be identified using the proposed model. Three distinctive aspects are discussed hereafter: proportions of design operations sequences, co-evolution and systematic approach.

Based on the previous findings and due to a specific setup of parameters of the computational study (Section 6.2) it has been both expected and coveted that the adaptive design simulations inherit higher overall proportions of analysis, evaluation and solution-related design operations, while simulations of innovative design exhibit higher proportions of synthesis and problem-related design operations. What was unknown prior to the simulations was which types of patterns cause the overall proportions of design operations. The new insights thus do not arise from the average proportions of design operations, but from the design operation sequences. For example, the analysis of sequence probabilities and proportions (Tables 6.7-6.9, Figure 6.9) can reveal the most evident differences between adaptive and innovative design projects, when it comes to approaching solution evaluation, solution synthesis or problem synthesis. Some of the distinctive patterns are shown in Figure 7.5.

In adaptive design, it was more likely and more frequent for the analysed and synthesised problems as well as analysed and synthesised solutions to be followed by solution evaluation when compared to innovative design. In addition, it was more frequent that solution analysis was preceded by problem and solution analysis, as well as solution synthesis and evaluation. On the other hand, solution evaluation is more likely to be followed by another solution evaluation design operations during innovative design. Analysis of three consecutive design operations reveals that both solution analysis and evaluation design operations frequently followed cycles of solution analysis during adaptive design and cycles of solution synthesis during innovative design. Innovative design is more likely to exhibit cycles of synthesis within the problem, the solution, as well as in-between the problem and the solution space. Moreover, new problem entities are more frequently immediately evaluated.

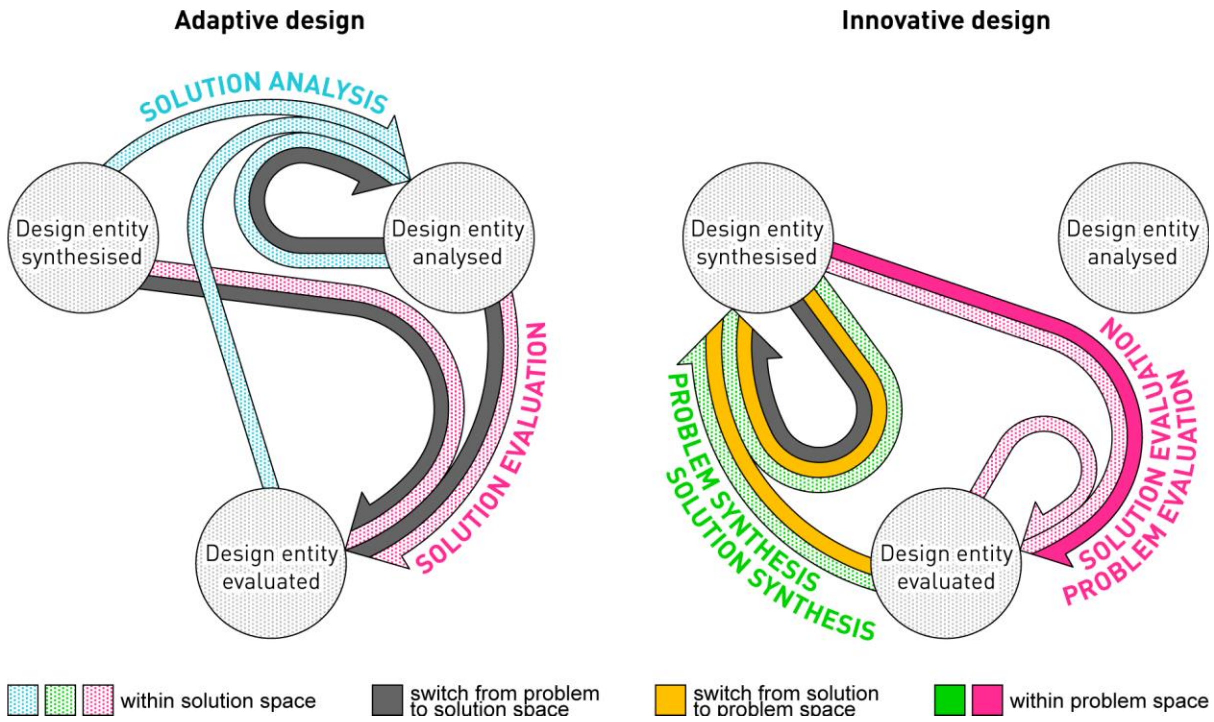

Figure 7.5 State transitions distinctive for adaptive (left) and innovative design (right)

The above-listed findings for the adaptive simulations can be summarised as follows: whenever problem entities were synthesised, teams would frequently perform problem analysis to clarify the new problem or evaluate the existing solutions against the new problem; and often when solution entities were synthesised, teams would systematically analyse and evaluate the new entities. Innovative design is less systematic and characterised by divergent sequences of problem and solution synthesis. Thus, when evaluated, the solution entities are likely to stimulate the synthesis of new problem entities. Such stimulation can be directly connected to the problem decomposition strategies observed by Liikkanen and Perttula [171]. In their model of problem decomposition, the more relevant knowledge the designers have, the more likely it is that the problem decomposition will be explicit (e.g. in adaptive design teams deliberately analyse the problems at the beginning of the design process). Hence, in adaptive design, teams formulate problems at the beginning, and then systematically analyse and evaluate solutions against these problems. On the other hand, implicit decomposition appears throughout the innovative conceptual design, as solution synthesis and evaluation lead to the introduction of new problem entities. Based on the studies conducted by Guindon [284] and Purcell et al. [285], Atman et al. [280] argue that such “opportunistic decomposition” is more effective for ill-structured nature of design problems (as innovative designs are by definition). After all, Cross [281] argues that in the context of creative design, it is the evaluation of solutions that is important to designers, not the analysis of the problem.

Different approaches to problem and solution synthesis are also directly related to problem-solution co-evolution. Wiltschnig et al. [67] emphasise that co-evolution episodes are closely related to the epistemic uncertainty, that is when designers are unsure about how to proceed based on their current state of knowledge. For example, their study has shown that problem space exploration was more likely to arise within co-evolution episodes than outside and that designers were frequently trying to synthesise solutions following uncertain exploration of problem space [67]. It can thus be hypothesised that due to the high levels of uncertainty attributed to innovative design, it exhibits significantly more co-evolution episodes, manifested in cycles of continuous synthesis of solution entities, which in return stimulate the generation of new problem entities, either directly by following solution synthesis, or indirectly through solution evaluation.

The uncertainty may as well be related to a more systematic approach observed in adaptive design. Namely, while both the computational studies of adaptive and innovative design have been set up with distinctive five steps (each having significantly different proportions of ASE and problem- and solution-related design operations), the average proportions of design operations and their sequences across the deciles are more pronounced throughout the adaptive design process (Figures 6.9-6.12). More precisely, divergent and convergent features of conceptual design are more evident in the averaged results of the adaptive design simulations. The average adaptive design process thus exhibits higher proportions of the divergent synthesis design operation at the beginning of conceptual design, before noticeably switching to convergent sequences of analysis and evaluation. Fricke [283] calls this “balanced search”, where designers alternate between diverging and converging, whereby the global search space is noticeably reduced, and solutions become more concrete. Likewise, Tversky and Chou [286] relate divergent thinking to producing more unrelated themes, and convergent thinking to producing interrelated elaboration od the same theme. As long as an idea is not fully elaborated, it cannot be evaluated as feasible. Moreover, they highlight that in the context of creative (innovative) design, it is not always easy to know whether to think divergently or convergently [286]. According to Toh et al. [238], the ability to converge faster during adaptive design can, among other things, be related to the designer’s familiarity with the (technical system) design.

Namely, better familiarisation was found to cause earlier fixation, and thus result in “less innovative designs”.

Interestingly, adaptive and innovative features can also be assigned to methods and people. For example, López-Mesa and Thompson [287] explain that adaptive divergent methods generate solutions by successive incremental improvement or through new combinations of existing sub-solutions, whereas innovative divergent methods facilitate the search of novel solutions by breaking the paradigm or by abstract association. On the other hand, adaptive convergent methods evaluate precise, numerical data and innovative convergent methods evaluate approximate, soft data. Similarly, adaptors tend to develop solutions that are improvements, under low uncertainty, whereas innovators tend to work at a higher level of uncertainty and with novel and less matured solutions [287].

8. CONCLUSION

The final chapter reflects on the aims, the hypothesis and the expected contributions introduced within the first chapter. It reemphasises the core findings developed throughout the thesis and links them to the initial research expectations. In addition, this chapter discusses the main research limitations and provides suggestions for conducting further research related to information processing in teams developing technical systems.

The research reported in the thesis attempts to improve understanding of designing in teams, particularly in the stage of conceptual design and from the perspective of information processing and interactions. In order to achieve this, a more specific research aim has been formed as follows: to review, develop and test models of team design activity in the development of technical systems, which will build on information processing and interactions appearing in team design activities in the conceptual design stage of the development. The main purpose of these models is to enhance decision-making and planning of technical systems development, by enabling both capturing and generation of data sets that reflect patterns in the design process distinctive for specific team compositions and working processes. This concluding chapter decomposes the main research aim, summarises the key findings and outlines the main contributions to the research of team conceptual design activity.

Prior to any theoretical development, a comprehensive review of engineering design models has been conducted. The review enveloped models of different levels of granularity, from the overall NPD and engineering design process models as contextually relevant, to the models of individual and team design activity as a means of a fine-grain analysis of designing. The review formulated research gaps and research questions that directed the development and testing of the model. The focus has from here on been set to patterns of analysis, synthesis and evaluation as fundamental information processes used to manipulate design entities within the problem space and the solution space, and how they change depending on the type of activity, the novelty of the product being designed and the progress of the conceptual design stage. Hence, reporting on the research background (Chapter 2) achieved the aim of reviewing models of team design activity.

Two models have been developed as part of the prescriptive research stage. The first, theoretical model has been formulated in the theoretical framework chapter (Chapter 3). The most relevant elements of the state-of-the-art models have been synthesised within a single theoretical framework. Definitions of analysis, synthesis and evaluation as design operations within both the problem and the solution space have been formulated and incorporated into a state-transition model of team conceptual design activity. The theoretical framework provides also the key variables, measures and visualisation templates to encompass the model.

The developed theoretical model has been tested as part of the first experimental study (Chapter 4), where it was used as a means of capturing, identifying and visualising design operation patterns in two types of team conceptual design activity. The first experimental study was conducted in the form of a verbal protocol analysis study. The coding scheme and measures for the observable information-processing acts in the design process have been formulated to match the theoretical foundations. Proportions of design operations and proportions and probabilities of their sequences have been investigated for a total of four teams performing ideation and concept review activities. The state-transition model enabled identification of both activity-specific patterns of design operation proportions and sequences (e.g. divergent cycles of problem and solution synthesis during ideation activity and convergent cycles of solution analysis and evaluation during concept review), as well as patterns common for the conceptual design stage (e.g. cycles of solution analysis and synthesis, and synthesis as means of switching between the spaces). It has been confirmed that, as the conceptual design stage progresses, the number of problem-related design operations decreases. The presented analysis also revealed that design teams utilise similar sequences of ASE design operations as they progressively explore the problem and the solution space during ideation. Despite the relatively low proportion of problem-related discussion during concept review, it has been shown that design operations in problem space play an important role within the refinement and convergence cycles. Hence, the conceptualisation of ASE as design operations performed similarly in the problem and the solution space provided new insights which complement the research on the co-evolution of the two spaces. Given the iterative nature of designing and the ill-defined nature of design problems in the conceptual design stage, it is unsurprising that neither the observed ideation or the concept review activities followed the microscale cycles of analysis-synthesis-evaluation or synthesis-analysis-evaluation, as suggested by some of the reviewed models.

Insights from the protocol analysis study have been utilised for the second part of the prescriptive research stage, the development of a mathematical model (Chapter 5). The relationships between the variables of design operation proportions and sequences have been identified within the protocol analysis data, and regression analysis was used to formalise these relationships. The mathematical model was developed by combining the regression equations and the theoretical assumptions proposed in Chapter 3. Before the mathematical model was applied in a second experimental study, its predictive power has been tested by simulating the results of the protocol analysis study.

After a satisfactory replication of the protocol analysis study results, the mathematical model has been utilised as a means of simulating proportions and sequences of design operations, based on a predefined setup of team conceptual design process (Chapter 6). An Excel-based computational tool has been developed for this purpose, and a test-case computational study has been conducted to compare the conceptual design stage of adaptive and innovative design projects. While the difference in segments and proportions of design operations were expected due to the experiment setup, the analysis of sequences of design operations has revealed some new insights. For example, the two simulation setups resulted in different patterns of sequences following the newly synthesised solution and problem entities, where the innovative design exhibited features that resemble the co-evolution process. On the other hand, the interplay between ASE and the cycles of two design operations throughout the conceptual design indicate that adaptive design follows a more systematic approach.

Finally, the discussion and validation chapter (Chapter 7) discusses the experimental results and the extent to which the purpose of the developed models has been met. The model has been tested both as a support for gathering and structuring data about team information processing and as a support for generating such data under new initial conditions. Specific working processes included two distinctive conceptual design activities (ideation and concept review), and two distinctive novelty levels of the technical system being developed (adaptive and innovative design). Specific team compositions have not been investigated; however, it is here argued that the same approach could be utilised for such research efforts.

From the design research perspective, it can be concluded that the scientific contribution is manifested in providing a valid description of team design activity and utilising the developed description in order to improve the understanding of team designing. Three main aspects of contribution can be outlined.

The first aspect of contribution concerns the state-transition theoretical framework and the accompanying theoretical model. It is argued that the developed state-transition model has fulfilled the purpose of supporting design research activity. The results of the protocol analysis and computational studies indicate that the theoretical model can be used to identify and analyse design process patterns such as sequences of design operations which are distinctive for specific working processes (e.g. divergent and convergent team conceptual design activities), as well as for the systematic approach to conceptual design. The experimental findings which could have been compared to the insights from the design research literature have been found aligned with the current understanding of designing in teams. The main advantage of the proposed theoretical model is its ability to map various sequences of ASE design operations which emerge during team design activity. Based on the listed findings, it can be argued that the developed theoretical model provides more flexibility when it comes to capturing and comparing the patterns of ASE design operations in the problem and the solution space and offers the potential of improving the understanding of the design process through either protocol analysis or computational studies of team conceptual design activity.

The second aspect of contribution concerns the mathematical model and the accompanying computational tool. It has been shown that if given the moving average proportions of three input parameters, the mathematical model can satisfactorily replicate proportions and sequences of design operations observed in the protocol analysis study. Moreover, the algorithm developed as part of extending the mathematical model into a computational simulation tool has included the concepts of iteration and uncertainty in order to distort the progress predefined by the systematic process steps. The test-case computational study has demonstrated the applicability of the mathematical model as a means of simulating differently set up stages and activities within the engineering design process.

Finally, the third aspect of contribution concerns the proposed visualisations of state transitions. It is argued that the visualisations augment the understanding of design operation patterns emerging during team conceptual design activities in two ways. First, as a summary of moves between ASE design operations within and in-between the problem and the solution space, where line thickness and colour coding are utilised to depict the frequency and types of transitions between the states of the explored design space. Second, as a template for mapping and visualising both the common and the activity-specific patterns of design operation sequences that can be identified during team conceptual designing. In addition, it is argued that the triangular visualisation of the moving average proportions of ASE design operations enables intuitive analysis, comparison and characterisation of processes performed by different teams. It can be used for both describing and investigating phenomena such as iteration, uncertainty, exploration and systematic approach to design.

Prior to reviewing, developing and testing the models, it was hypothesised that the modelling and simulation of information processing and interactions of individuals that perform teamwork activities, enables understanding of the features of innovative and adaptive technical systems development and thus facilitate research, planning and management of development projects. As discussed above, understanding has been improved not only for the features of innovative and adaptive technical systems development but also for ideation and concept review activities and teamwork throughout the conceptual design stage in general. Better understanding derived from the obtained findings, together with the potential of simulating new insights, can help researchers and project managers in developing and prescribing the most appropriate and efficient methods and tools for the particular design tasks. However, the potential of enhancing decision-making in planning and management is yet to be further explored. At this point, additional research must be conducted to ensure that the models are robust, reliable and validated and that the designed support tool is easy to implement in design and project management practice. Guided by the recommendation found within the DRM methodology [30], the presented results are instead seen as part of a sound foundation for the effective and efficient realisation of tool development and potential implementation of research results into engineering design practice.

8.1. Research limitations

Research limitations are primarily related to the quantity and quality of data collected through the protocol analysis study and generated via the computational study. Although statistically significant differences have been identified between two types of team conceptual design activities, larger sample sizes are preferable in future studies to validate the hypothesised claims and patterns. Using larger sample sizes and performing protocol analysis studies of adaptive and innovative projects would also result in more precise regression models and better predictive power of the computational simulation tool. In addition, due to the scope of the dissertation and space available, only a single test-case computational study has been reported. Additional studies are required to build data sets sufficient for further in-depth analyses of team design activity. For the computational tool to be entirely useful as a means of approximating the design process, the simulator must be fully verified, validated and calibrated, particularly in terms of its implementation, accuracy and precision.

Moreover, the presented research has examined only the distribution and sequences of verbalised ASE design operations, neglecting both the possibly significant effects of non-verbalised acts or investigating the rationale for the transitions inside and in-between the problem and the solution space. As pointed out in the introductory chapter, not taking into account the non-verbalised, as well as the non-observable processes results in grasping only a single layer of a multi-layered phenomenon such as team designing. Experimental studies encompassing a more comprehensive observational approaches and focused strictly on the reasoning for particular design operations could provide a further understanding of the patterns identified during the team conceptual design activities.

An additional limitation has been recognised in the lack of describing the context of team discussions. Namely, the derived patterns are based solely on the strings of design operations codes. For instance, when capturing a sequence of solution analysis following solution synthesis, it was not examined if the two design operations involve the same design entity. The context is also directly related to understanding iteration, that is, when and how iteration appears during team design activities. Hence, in the future, the additional dimension of discussion context could help in both capturing and simulating patterns of ASE design operations related to a single or a group of related design entities in the problem and the solution space. For example, IMoD [218] utilises three dimensions to link the process, the design spaces and the outcomes, thus enabling the tracking of activity patterns related to individual design entities. Moreover, the Linkography method [28], [248] can also be used to mark segments of activity which are associated with the evolution of a single design entity.

Similarly, the study is limited in addressing design operations solely on the team level. Hence, the protocol data does not provide information on team members which took part in the sequences of design operations. Another issue which has not been investigated is the relation between the roles of individual team members and their contribution to performing design operations. It is suggested that further studies include an additional layer to the coding process, which would provide data on who is taking a turn.

Finally, interactions encompassed by the model include only the interplay between design operations. Although they might have a significant effect on the investigated aspects of the design process, the interactions of team members, such as turn-taking or verbal engagement [288] have not been considered. Capturing the interaction of team members would add a layer of information to the protocols, which can be coupled with the analysis of proportions and sequences of design operations to provide a richer picture of team designing.

8.2. Future work

Besides the additional work required to address the research limitations, there exist also several possible directions for further developments and research extensions. For example, the proposed state-transition model can be used to investigate the effects of design methods, environments and team members' characteristics (background, experience, motivation, personality, problem-solving style, etc.) on the patterns of ASE design operations performed in the problem and the solution space. Earlier studies have shown that the methods used during team design activities [207], designers' background [55], [206] and the type of communication (virtual vs face-to-face) [27] can affect the team's design process.

Future work might also investigate the applicability of the model to describe team activities in different stages of the design process. In the presented study the focus was set on conceptual design activities since the conceptual design stage has been regarded as critical for the co-development of the problem and the solution space. Nonetheless, it is argued that team activities in the stages of planning, embodiment or detailed design could also be investigated using the proposed models.

Besides the design novelty levels, different engineering design projects are likely to encompass tasks of varying degrees of complexity, include teams of different sizes and team members of different expertise. These dimensions are likely to alter patterns of performing design operations at different points in the development process. Future studies should utilise state-transition modelling to comprehensively investigate the effects that these dimensions have on information processing and interactions between team members.

Finally, the rationale for the probabilities of specific transitions (design operations) between the states could be hypothesised and investigated. For example, synthesis of a new design entity might be studied as a result of association, transformation or memory-based thinking processes of designers [56], [248]. Similarly, analysis as a result of questioning and misunderstanding [54], [56], and evaluation resulting from the need for narrowing the design space (see, e.g. the research studies conducted by McComb et al. [96], and Yilmaz and Daly [247]) can be investigated in the future.

REFERENCES

[1] Markham SK. The Impact of Front-End Innovation Activities on Product Performance. Journal of Product Innovation Management. 2013;30(S1):77–92. doi. 10.1111/jpim.12065.

[2] Slater SF, Mohr JJ, Sengupta S. Radical Product Innovation Capability: Literature Review, Synthesis, and Illustrative Research Propositions. Journal of Product Innovation Management. 2014;31(3):552–66. doi. 10.1111/jpim.12113.

[3] Ames E. Research, Invention, Development and Innovation. The American Economic Review. 1961;51(3):370–81.

[4] Garcia R, Calantone R. A critical look at technological innovation typology and innovativeness terminology: A literature review. Journal of Product Innovation Management. 2002;19(2):110–32. doi. 10.1016/S0737-6782(01)00132-1.

[5] Cooper RG, Kleinschmidt EJ. An Investigation into the New Product Process: Steps, Deficiencies, and Impact. Journal of Product Innovation Management. 1986;3(2):71–85. doi. 10.1111/1540-5885.320071.

[6] Page AL. Assessing New Product Development Practices and Performance: Establishing Crucial Norms. Journal of Product Innovation Management. 1993;10(4):273–90. doi. 10.1111/1540-5885.1040273.

[7] Griffin A. PDMA research on new product development practices: updating trends and benchmarking best practices. Journal of Product Innovation Management. 1997;14(6):429–58. doi. 10.1111/1540-5885.1460429.

[8] Schmidt JB, Sarangee KR, Montoya MM. Exploring New Product Development Project Review Practices. Journal of Product Innovation Management. 2009;26(5):520–35. doi. 10.1111/j.1540-5885.2009.00678.x.

[9] Barczak G, Griffin A, Kahn KB. Perspective: Trends and drivers of success in NPD practices: Results of the 2003 PDMA best practices study. Journal of Product Innovation Management. 2009;26(1):3–23. doi. 10.1111/j.1540-5885.2009.00331.x.

[10] Anthony SD. Innovation Is a Discipline, Not a Cliché. Harvard Business Review. 2012. Available from: https://hbr.org/2012/05/four-innovation-misconceptions [cited 2019 Mar 1];

[11] Edmondson AC, Nembhard IM. Product development and learning in project teams: The challenges are the benefits. Journal of Product Innovation Management. 2009;26(2):123–138. doi. 10.1111/j.1540-5885.2009.00341.x.

[12] Crawford M, Di Benedetto A. New Products Management. 10th ed. New York: McGraw-Hill; 2010.

[13] Kleinsmann M, Deken F, Dong A, Lauche K. Development of design collaboration skills. Journal of Engineering Design. 2012;23(7):485–506. doi. 10.1080/09544828.2011.619499.

[14] Badke-Schaub P, Frankenberger E. Analysis of design projects. Design Studies. 1999;20(5):465–80. doi. 10.1016/S0142-694X(99)00017-4.

[15] Ostergaard KJ, Summers JD. Development of a systematic classification and taxonomy of collaborative design activities. Journal of Engineering Design. 2009;20(1):57–81. doi. 10.1080/09544820701499654.

[16] Crowder RM, Robinson M a., Hughes HPN, Sim Y-W. The Development of an Agent-Based Modeling Framework for Simulating Engineering Team Work. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans. 2012;42(6):1425–39.

[17] Hsu Y. Work values, conflict, and team cooperation among engineering designers. Journal of Engineering Design. 2017;28(10–12):799–820. doi. 10.1080/09544828.2017.1397268.

[18] Robinson M a., Sparrow PR, Clegg C, Birdi K. Design engineering competencies: future requirements and predicted changes in the forthcoming decade. Design Studies. 2005;26(2):123–53. doi. 10.1016/j.destud.2004.09.004.

[19] Han Y-L, Cook K, Mason G, Shuman TR. Enhance Engineering Design Education in the Middle Years With Authentic Engineering Problems. Journal of Mechanical Design. 2018;140(12):122001-122001–9. doi. 10.1115/1.4040880.

[20] Hultén M, Artman H, House D. A model to analyse students' cooperative idea generation in conceptual design. International Journal of Technology and Design Education. 2018;28(2):451–70. doi. 10.1007/s10798-016-9384-x.

[21] Hey J, Pelt A Van, Agogino A, Beckman S. Self-Reflection: Lessons Learned in a New Product Development Class. Journal of Mechanical Design. 2007;129(7):668–76. doi. 10.1115/1.2722781.

[22] Cross N, Clayburn Cross A. Observations of teamwork and social processes in design. Design Studies. 1995;16(2):143–70. doi. 10.1016/0142-694X(94)00007-Z.

[23] Dinar M, Shah JJ, Cagan J, Leifer L, Linsey J, Smith SM, et al. Empirical Studies of Designer Thinking: Past, Present, and Future. Journal of Mechanical Design. 2015;137(2):021101. doi. 10.1115/1.4029025.

[24] Sosa R. Computational Modelling of Teamwork in Design. In: Cash P, Stanković T, Štorga M, editors. Experimental Design Research: Approaches, Perspectives, Applications. Cham: Springer; 2016. p. 173–86. doi. 10.1007/978-3-319-33781-4_10.

[25] Macmillan S, Steele J, Austin S, Kirby P, Robin Spence. Development and verification of a generic framework for conceptual design. Design Studies. 2001;22(2):169–91. doi. 10.1016/S0142-694X(00)00025-9.

[26] Gero JS, Kannengiesser U. The function-behaviour-structure ontology of design. In: Chakrabarti A, Blessing L, editors. An Anthology of Theories and Models of Design. London: Springer; 2014. p. 263–83. doi. 10.1007/978-1-4471-6338-1_13.

[27] Gero JS, Kan JWT. Scientific Models from Empirical Design Research. In: Cash P, Stanković T, Štorga M, editors. Experimental Design Research: Approaches, Perspectives, Applications. Cham: Springer; 2016. p. 253–70. doi. 10.1007/978-3-319-33781-4_14.

[28] Goldschmidt G. Linkography: Unfolding the Design Process. Cambridge, MA: The MIT Press; 2014.

[29] Lahti H, Seitamaa-Hakkarainen P, Hakkarainen K. Collaboration patterns in computer supported collaborative designing. Design Studies. 2004;25(4):351–71. doi. 10.1016/j.destud.2003.12.001.

[30] Blessing LTM, Chakrabarti A. DRM, a Design Research Methodology. London: Springer; 2009. doi. 10.1007/978-1-84882-587-1.

[31] Horváth I. Conceptual design: Inside and outside. In: Rohatynski R, editor. Proceedings of the 2nd International Seminar and Workshop on Engineering Design in Integrated Product Development - EDIProD 2000. Zielona Gora: UZG; 2000. p. 63–72.

[32] Maarten Bonnema G, van Houten FJAM. Use of models in conceptual design. Journal of Engineering Design. 2006;17(6):549–62. doi. 10.1080/09544820600664994.

[33] Komoto H, Tomiyama T. A framework for computer-aided conceptual design and its application to system architecting of mechatronics products. CAD Computer Aided Design. 2012;44(10):931–46. doi. 10.1016/j.cad.2012.02.004.

[34] Shah JJ, Kulkarni S V., Vargas-Hernandez N. Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments. Journal of Mechanical Design. 2000;122(4):377–84. doi. 10.1115/1.1315592.

[35] Vuletic T, Duffy A, Hay L, McTeague C, Pidgeon L, Grealy M. The challenges in computer supported conceptual engineering design. Computers in Industry. 2018;95:22–37. doi. 10.1016/j.compind.2017.11.003.

[36] Jin Y, Benami O. Creative patterns and stimulation in conceptual design. Artificial Intelligence for Engineering Design, Analysis and Manufacturing. 2010;24(2):191–209. doi. 10.1017/S0890060410000053.

[37] Reich Y, Ullmann G, Van Der Loos M, Leifer L. Coaching product development teams: A conceptual foundation for empirical studies. Research in Engineering Design. 2009;19(4):205–22. doi. 10.1007/s00163-008-0046-1.

[38] Cohen SG, Bailey DE. What makes teams work: Group effectiveness research from the shop floor to the executive suite. Journal of Management. 1997;23(3):239–90. doi. 10.1177/014920639702300303.

[39] Kozlowski SWJ, Bell BS. Work groups and teams in organizations: Review update. In: Schmitt N, Highhouse S, editors. Handbook of Psychology. 2nd ed. Hoboken, NJ: Wiley; 2013. p. 412–69.

[40] Denton HG. Multidisciplinary team-based project work: planning factors. Design Studies. 1997;18(2):155–70. doi. 10.1016/S0142-694X(97)85458-0.

[41] Pahl G, Beitz W, Feldhusen J, Grote K-H. Engineering Design: A Systematic Approach. 3rd ed. London: Springer-Verlag; 2007. doi. 10.1007/978-1-84628-319-2.

[42] Howard TJ, Culley SJ, Dekoninck E. Describing the creative design process by the integration of engineering design and cognitive psychology literature. Design Studies. 2008;29(2):160–80. doi. 10.1016/j.destud.2008.01.001.

[43] Court AW. Improving creativity in engineering design education. European Journal of Engineering Education. 1998;23(2):141–54. doi. 10.1080/03043799808923493.

[44] Fitch P, Cooper JS. Life-cycle modeling for adaptive and variant design. Part 1: Methodology. Research in Engineering Design. 2005;15(4):216–28. doi. 10.1007/s00163-004-0055-7.

[45] Hey J, Yu J, Agogino AM. Design Team Framing: Paths and Principles. In: Proceedings of the 20th International Conference on Design Theory and Methodology; New York, USA, 03-06.08.2008. ASME; 2008. p. 409–20. doi. 10.1115/DETC2008-49383.

[46] Cash P, Štorga M. Multifaceted assessment of ideation: using networks to link ideation and design activity. Journal of Engineering Design. 2015;26(10–12):391–415. doi. 10.1080/09544828.2015.1070813.

[47] Wild PJ, McMahon C, Darlington M, Liu S, Culley S. A diary study of information needs and document usage in the engineering domain. Design Studies. 2010;31(1):46–73. doi. 10.1016/j.destud.2009.06.002.

[48] Robinson MA. How design engineers spend their time: Job content and task satisfaction. Design Studies. 2012;33(4):391–425. doi. 10.1016/j.destud.2012.03.002.

[49] Wynn D, Clarkson P. Process models in design and development. Research in Engineering Design. 2017;29(2):161–202. doi. 10.1007/s00163-017-0262-7.

[50] Andreasen MM, Hansen CT, Cash P. Conceptual design: Interpretations, mindset and models. Conceptual Design: Interpretations, Mindset and Models. Cham: Springer; 2015. doi. 10.1007/978-3-319-19839-2.

[51] Atman CJ, Kilgore D, Mckenna A. Characterizing design learning: A mixed-methods study of engineering designers’ use of language. Journal of Engineering Education. 2008;97(3):309–26. doi. 10.1002/j.2168-9830.2008.tb00981.x.

[52] Oyama K, Learmonth G, Chao R. Applying complexity science to new product development: Modeling considerations, extensions, and implications. Journal of Engineering and Technology Management. 2015;35:1–24. doi. 10.1016/j.jengtecman.2014.07.003.

[53] Lawson B, Dorst K. Design Expertise. Oxford: Architectural Press; 2009.

[54] Stempfle J, Badke-Schaub P. Thinking in design teams - an analysis of team communication. Design Studies. 2002;23(5):473–96. doi. 10.1016/S0142-694X(02)00004-2.

[55] Jiang H, Gero JS, Yen CC. Exploring designing styles using a problem–solution division. In: Gero J, editor. Design Computing and Cognition '12. Dordrecht: Springer; 2014. p. 79–94. doi. 10.1007/978-94-017-9112-0_5.

[56] Sauder J, Jin Y. A qualitative study of collaborative stimulation in group design thinking. Design Science. 2016;2(e4). doi. 10.1017/dsj.2016.1.

[57] Dong A, Kleinsmann MS, Deken F. Investigating design cognition in the construction and enactment of team mental models. Design Studies. 2013;34(1):1–33. doi. 10.1016/j.destud.2012.05.003.

[58] Eris O, Martelaro N, Badke-Schaub P. A comparative analysis of multimodal communication during design sketching in co-located and distributed environments. Design Studies. 2014;35(6):559–92. doi. 10.1016/j.destud.2014.04.002.

[59] Wulvik A, Jensen MB, Steinert M. Temporal static visualisation of transcripts for pre-analysis of video material: Identifying modes of information sharing. In: Christensen BT, Ball LJ, Halskov K, editors. Analysing Design Thinking: Studies of Cross-Cultural Co-Creation. London: CRC Press; 2017. doi. 10.1201/9781315208169.

[60] Cash P, Dekoninck EA, Ahmed-Kristensen S. Supporting the development of shared understanding in distributed design teams. Journal of Engineering Design. 2017;28(3):147–70. doi. 10.1080/09544828.2016.1274719.

[61] Toh CA, Miller SR. Creativity in design teams: the influence of personality traits and risk attitudes on creative concept selection. Research in Engineering Design. 2016;27(1):73–89. doi. 10.1007/s00163-015-0207-y.

[62] D'souza N, Dastmalchi MR. Creativity on the move: Exploring little-c (p) and big-C (p) creative events within a multidisciplinary design team process. Design Studies. 2016;46:6–37. doi. 10.1016/j.destud.2016.07.003.

[63] Deken F, Kleinsmann M, Aurisicchio M, Lauche K, Bracewell R. Tapping into past design experiences: Knowledge sharing and creation during novice-expert design consultations. Research in Engineering Design. 2012;23(3):203–18. doi. 10.1007/s00163-011-0123-8.

[64] Stumpf SC, McDonnell JT. Talking about team framing: Using argumentation to analyse and support experiential learning in early design episodes. Design Studies. 2002;23(1):5–23. doi. 10.1016/S0142-694X(01)00020-5.

[65] Kurakawa K. A scenario-driven conceptual design information model and its formation. Research in Engineering Design. 2004;15(2):122–37. doi. 10.1007/s00163-004-0050-z.

[66] Brissaud D, Garro O, Poveda O. Design process rationale capture and support by abstraction of criteria. Research in Engineering Design. 2003;14(3):162–72. doi. 10.1007/s00163-003-0038-0.

[67] Wiltschnig S, Christensen BT, Ball LJ. Collaborative problem-solution co-evolution in creative design. Design Studies. 2013;34(5):515–42. doi. 10.1016/j.destud.2013.01.002.

[68] Tang HH, Lee YY, Gero JS. Comparing collaborative co-located and distributed design processes in digital and traditional sketching environments: A protocol study using the function-behaviour-structure coding scheme. Design Studies. 2011;32(1):1–29. doi. 10.1016/j.destud.2010.06.004.

[69] Culley SJ. Revisiting Design as an Information Processing Activity. In: Chakrabarti A, Blessing L, editors. An Anthology of Theories and Models of Design. London: Springer; 2014. p. 371–94. doi. 10.1007/978-1-4471-6338-1_18.

[70] Hubka V, Eder WE. Design Science. London: Springer-Verlag; 1996. doi. 10.1007/978-1-4471-3091-8.

[71] Eder WE. Information systems for designers. In: Hubka V, editor. Proceedings of ICED89, International Conference on Engineering Design; Harrogate, UK, 22-25.08.1989. Bury St Edmunds: Mechanical Engineering Publication Ltd; 1989. p. 1307–19.

[72] Hales C, Gooch S. Managing Engineering Design. London: Springer; 2004. doi. 10.1007/978-0-85729-394-7.

[73] Bracewell R, Wallace K, Moss M, Knott D. Capturing design rationale. CAD Computer Aided Design. 2009;41(3):173–86. doi. 10.1016/j.cad.2008.10.005.

[74] Wallace K, Ahmed S. How Engineering Designers Obtain Information. In: Lindemann U, editor. Human Behaviour in Design. Berlin, Heidelberg: Springer; 2003. p. 184–94. doi. 10.1007/978-3-662-07811-2_19.

[75] Wodehouse AJ, Ion WJ. Information use in conceptual design: Existing taxonomies and new approaches. International Journal of Design. 2010;4(3):53–65.

[76] Ensici A, Badke-Schaub P. Information behavior in multidisciplinary design teams. In: Culley SJ, Hicks BJ, McAloone TC, Howard TJ, Badke-Schaub P, editors. Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 7: Human Behaviour in Design; Lyngby/Copenhagen, Denmark, 15-19.08.2011. The Design Society; 2011. p. 414–23.

[77] Ullman DG. Toward the ideal mechanical engineering design support system. Research in Engineering Design. 2002;13(2):55–64. doi. 10.1007/s00163-001-0007-4.

[78] Crilly N, Cardoso C. Where next for research on fixation, inspiration and creativity in design? Design Studies. 2017;50:1–38. doi. 10.1016/j.destud.2017.02.001.

[79] Ahmed S, Wallace KM, Blessing LTM. Understanding the differences between how novice and experienced designers approach design tasks. Research in Engineering Design. 2003;14(1):1–11. doi. 10.1007/s00163-002-0023-z.

[80] Björklund TA. Initial mental representations of design problems: Differences between experts and novices. Design Studies. 2013;34(2):135–60. doi. 10.1016/j.destud.2012.08.005.

[81] Gero JS, Tang HH. The differences between retrospective and concurrent protocols in revealing the process-oriented aspects of the design process. Design Studies. 2001;22(3):283–95. doi. 10.1016/S0142-694X(00)00030-2.

[82] Horváth I. A treatise on order in engineering design research. Research in Engineering Design. 2004;15(3):155–81. doi. 10.1007/s00163-004-0052-x.

[83] Maher M Lou, Tang H. Co-evolution as a computational and cognitive model of design. Research in Engineering Design. 2003;14(1):47–64. doi. 10.1007/s00163-002-0016-y.

[84] Ericsson KA, Simon HA. Protocol analysis: Verbal reports as data. Cambridge, MA: MIT Press; 1993.

[85] Torlind, P. Sonalkar, N. Bergstrom, M. Blanco, E. Hicks, B. McAlpine H. Lessons Learned and Future Challenges for Design Observatory Research. In: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 2, Design Theory and Research Methodology; Palo Alto, CA, USA, 24-27.08.2009. 2009.

[86] Simon HA, Newell A. Human problem solving: The state of the theory in 1970. American Psychologist. 1971;26(2):145–59. doi. 10.1037/h0030806.

[87] Woodbury RF, Burrow AL. Whither design space? Artificial Intelligence for Engineering Design, Analysis and Manufacturing. 2006;20(2):63–82. doi. 10.1017/S0890060406060057.

[88] Goel AK, Helms ME. Theories, Models, Programs, and Tools of Design: Views from Artificial Intelligence, Cognitive Science, and Human-Centered Computing. In: Chakrabarti A, Blessing L, editors. An Anthology of Theories and Models of Design. London: Springer; 2014. p. 417–32. doi. 10.1007/978-1-4471-6338-1_20.

[89] Levitt RE. Toward analysis tools for the engineering process. Artificial Intelligence for Engineering Design, Analysis and Manufacturing. 1998;12(1):77–78. doi. 10.1017/S0890060498121157.

[90] Shah JJ, Smith SM, Vargas-Hernandez N. Metrics for measuring ideation effectiveness. Design Studies. 2003;24(2):111–34. doi. 10.1016/S0142-694X(02)00034-0.

[91] Kavakli M, Gero JS. The structure of concurrent cognitive actions: a case study on novice and expert designers. Design Studies. 2002;23(1):25–40. doi. 10.1016/S0142-694X(01)00021-7.

[92] Wardak D. Gestures orchestrating the multimodal development of ideas in educational design team meetings. Design Studies. 2016;47:1–22. doi. 10.1016/j.destud.2016.08.001.

[93] Behoora I, Tucker CS. Machine learning classification of design team members' body language patterns for real time emotional state detection. Design Studies. 2015;39:100–27. doi. 10.1016/j.destud.2015.04.003.

[94] Visser W, Maher M Lou. The role of gesture in designing. Artificial Intelligence for Engineering Design, Analysis and Manufacturing. 2011;25(3):213–20. doi. 10.1017/S0890060411000047.

[95] Tory M, Staub-French S, Po BA, Wu F. Physical and Digital Artifact-Mediated Coordination in Building Design. Computer Supported Cooperative Work (CSCW). 2008;17(4):311–51. doi. 10.1007/s10606-008-9077-4.

[96] McComb C, Cagan J, Kotovsky K. Lifting the Veil: Drawing insights about design teams from a cognitively-inspired computational model. Design Studies. 2015;40:119–42. doi. 10.1016/j.destud.2015.06.005.

[97] Cross N. Design cognition: results from protocol and other empirical studies of design activity. In: Newstatter W, McCracken M, editors. Design Knowing and Learning: Cognition in Design Education. Elsevier; 2001. p. 79–103. doi. 10.1016/B978-008043868-9/50005-X.

[98] Kan JWT, Gero JS. Quantitative Methods for Studying Design Protocols. Quantitative Methods for Studying Design Protocols. 2017. doi. 10.1007/978-94-024-0984-0.

[99] Chiu I, Shu LH. Potential Limitations of Verbal Protocols in Design Experiments. In: Proceedings of the 22nd International Conference on Design Theory and Methodology; Special Conference on Mechanical Vibration and Noise; Montreal, Quebec, Canada, 15-18.08.2010. ASME; 2010. p. 287–96. doi. 10.1115/DETC2010-28675.

[100] Coley F, Houseman O, Roy R. An introduction to capturing and understanding the cognitive behaviour of design engineers. Journal of Engineering Design. 2007;18(4):311–25. doi. 10.1080/09544820600963412.

[101] Hay L, Duffy AHB, McTeague C, Pidgeon LM, Vuletic T, Grealy M. A systematic review of protocol studies on conceptual design cognition: Design as search and exploration. Design Science. 2017;3:e10. doi. 10.1017/dsj.2017.11.

[102] Sim SK, Duffy AHB. Towards an ontology of generic engineering design activities. Research in Engineering Design. 2003;14(4):200–23. doi. 10.1007/s00163-003-0037-1.

[103] Kroll E. Design theory and conceptual design: Contrasting functional decomposition and morphology with parameter analysis. Research in Engineering Design. 2013;24(2):165–83. doi. 10.1007/s00163-012-0149-6.

[104] French MJ. Conceptual Design for Engineers. London: Springer; 1999. doi. 10.1007/978-1-4471-3627-9.

[105] Anderson KJB, Courter SS, McGlamery T, Nathans-Kelly TM, Nicometo CG. Understanding engineering work and identity: A cross-case analysis of engineers within six firms. Engineering Studies. 2010;2(3):153–74. doi. 10.1080/19378629.2010.519772.

[106] Yang X, Dong A, Helander M. The analysis of knowledge integration in collaborative engineering teams. Journal of Engineering Design. 2012;23(2):119–33. doi. 10.1080/09544828.2011.567979.

[107] Sonalkar N, Mabogunje A, Leifer L. Developing a visual representation to characterize moment-to-moment concept generation in design teams. International Journal of Design Creativity and Innovation. 2013;1(2):93–108. doi. 10.1080/21650349.2013.773117.

[108] Ziv-Av A, Reich Y. SOS - Subjective objective system for generating optimal product concepts. Design Studies. 2005;26(5):509–33. doi. 10.1016/j.destud.2004.12.001.

[109] Frankenberger E, Auer P. Standardized observation of team-work in design. Research in Engineering Design. 1997;9(1):1–9. doi. 10.1007/BF01607053.

[110] Nik Ahmad Ariff NS, Badke-Schaub P, Eris O, Suib SSS. A framework for reaching common understanding during sketching in design teams. In: Proceedings of the 12th International Design Conference DESIGN 2012; Dubrovnik, Croatia, 21-24.05.2012. Zagreb: The Design Society; 2012. p. 1525–33.

[111] Karniel A, Reich Y. Managing the Dynamics of New Product Development Processes: A New Product Lifecycle Management Paradigm. London: Springer; 2011. doi. 10.1007/978-0-85729-570-5.

[112] Hubka V, Eder E. Engineering Design. Zürich: Heurista; 1992.

[113] Cash P, Stanković T, Štorga M. Experimental Design Research: Approaches, Perspectives, Applications. Cham: Springer; 2016. doi. 10.1007/978-3-319-33781-4.

[114] Dinar M, Summers JD, Shah J, Park YS. Evaluation of empirical design studies and metrics. In: Cash P, Stanković T, Štorga M, editors. Experimental Design Research: Approaches, Perspectives, Applications. Cham: Springer; 2016. p. 13–39. doi. 10.1007/978-3-319-33781-4_2.

[115] Valkenburg R, Dorst K. The reflective practice of design teams. Design Studies. 1998;19(3):249–71. doi. 10.1016/S0142-694X(98)00011-8.

[116] Hubka V, Eder WE. Theory of Technical Systems: A Total Concept Theory for Engineering Design. Berlin Heidelberg: Springer; 1988.

[117] McMahon C. Design Informatics: Supporting Engineering Design Processes with Information Technology. Journal of the Indian Institute of Science. 2015;95(4):365–77.

[118] Browning TR, Ramasesh R V. A Survey of Activity Network-Based Process Models for Managing Product Development Projects. Production and Operations Management. 2007;16(2):217–40. doi. 10.1111/j.1937-5956.2007.tb00177.x.

[119] Sharafi A, Wolfenstetter T, Wolf P, Krcmar H. Comparing product development models to identify process coverage and current gaps: A literature review. In: IEEM2010 - IEEE International Conference on Industrial Engineering and Engineering Management; Macao, China, 07-10.12.2010. 2010. p. 1732–6. doi. 10.1109/IEEM.2010.5674575.

[120] Wynn DC. Model-based approaches to support process improvement in complex product development [PhD Thesis]. University of Cambridge; 2007. doi. 10.17863/CAM.13990.

[121] Cooper RG. Stage-gate systems: A new tool for managing new products. Business Horizons. 1990;33(3):44–54. doi. 10.1016/0007-6813(90)90040-I.

[122] Cooper RG. Perspective: The Stage-Gate® Idea-to-Launch Process—Update, What's New, and NexGen Systems. Journal of Product Innovation Management. 2008;25(3):213–32. doi. 10.1111/j.1540-5885.2008.00296.x.

[123] Hart SJ, Baker MJ. The Multiple Convergent Processing Model of New Product Development. International Marketing Review. 1994;11(1):77–92. doi. 10.1108/02651339410057536.

[124] Fairlie-Clarke T, Muller M. An activity model of the product development process. Journal of Engineering Design. 2003;14(3):247–72. doi. 10.1080/0954482031000091040.

[125] Cooper RG, Sommer AF. The Agile-Stage-Gate Hybrid Model: A Promising New Approach and a New Research Opportunity. Journal of Product Innovation Management. 2016;33(5):513–26. doi. 10.1111/jpim.12314.

[126] Cooper RG. Agile–Stage-Gate Hybrids. Research-Technology Management. 2016;59(1):21–9. doi. 10.1080/08956308.2016.1117317.

[127] Booz, Allen & Hamilton. New Product Management for the 1980's. New York: Booz, Allen & Hamilton; 1982.

[128] Fortenberry JL. Booz, Allen, and Hamilton's New Product Process. In: Nonprofit Marketing. Burlington, MA: Jones & Bartlett Learning; 2013. p. 11–8.

[129] Song XM, Montoya-Weiss MM. Critical Development Activities for Really New versus Incremental Products. Journal of Product Innovation Management. 1998;15(2):124–35. doi. 10.1111/1540-5885.1520124.

[130] Kahn KB. The PDMA handbook of new product development. 3rd ed. Hoboken, NJ: John Wiley & Sons, Inc.; 2013.

[131] Akroush MN. An empirical model of new product development process: phases, antecedents and consequences. International Journal of Business Innovation and Research. 2011;6(1):47–75. doi. 10.1504/ijbir.2012.044257.

[132] Im S, Nakata C, Park H, Ha Y-W. Determinants of Korean and Japanese New Product Performance: An Interrelational and Process View. Journal of International Marketing. 2003;11(4):81–112. doi. 10.1509/jimk.11.4.81.20149.

[133] Lagrosen S. Customer involvement in new product development: A relationship marketing perspective. European Journal of Innovation Management. 2005;8(4):424–36. doi. 10.1108/14601060510627803.

[134] Durmuşoğlu SS, Barczak G. The use of information technology tools in new product development phases: Analysis of effects on new product innovativeness, quality, and market performance. Industrial Marketing Management. 2011;40(2):321–30. doi. 10.1016/j.indmarman.2010.08.009.

[135] Frishammar J, Ylinenpää H. Managing information in new product development: A conceptual review, research propositions and tentative model. International Journal of Innovation Management. 2007;11(04):441–67. doi. 10.1142/S1363919607001825.

[136] Archer LB. Technological innovation - a methodology. London: Inforlink Ltd; 1971.

[137] Pugh S. Total Design: Integrated Methods for Successful Product Engineering. 1st ed. Wokingham: Addison-Wesley; 1991.

[138] Andreasen MM, Hein L. Integrated product development. London: Springer; 1987.

[139] Ulrich KT, Eppinger SD. Product Design and Development. 6th ed. New York: McGraw-Hill; 2015.

[140] Buijs J. Modelling product innovation processes, from linear logic to circular chaos. Creativity and Innovation Management. 2003;12(2):76–93. doi. 10.1111/1467-8691.00271.

[141] Hauptman O, Hirji KK. The influence of process concurrency on project outcomes in product development: an empirical study of cross-functional teams. IEEE Transactions on Engineering Management. 1996;43(2):153–64. doi. 10.1109/17.509981.

[142] Zhang H, Basadur TM, Schmidt JB. Information distribution, utilization, and decisions by new product development teams. Journal of Product Innovation Management. 2014;31(S1):189–204. doi. 10.1111/jpim.12200.

[143] Pentina I, Strutton D. Information processing and new product success: A meta-analysis. European Journal of Innovation Management. 2007;10(2):149–75. doi. 10.1108/14601060710745233.

[144] Lynn G, Simpson J, Souder W. Effects of Organizational Learning and Information-Processing Behaviors on New Product Success. Marketing Letters. 1997;8(1):33–9. doi. 10.1023/A:1007981109972.

[145] Ottum B. The role of market information in new product success/failure. Journal of Product Innovation Management. 1997;14(4):258–73. doi. 10.1016/S0737-6782(97)00013-1.

[146] Lynn GS, Reilly RR, Akgiin AHE. Knowledge management in new product teams: practices and outcomes. IEEE Transactions on Engineering Management. 2000;47(2):221–31. doi. 10.1109/17.846789.

[147] Akgün AE, Lynn GS, Reilly R. Multi-dimensionality of learning in new product development teams. European Journal of Innovation Management. 2002;5(2):57–72. doi. 10.1108/14601060210428168.

[148] Li W, Moon YB. Modeling and managing engineering changes in a complex product development process. The International Journal of Advanced Manufacturing Technology. 2012;63(9–12):863–74. doi. 10.1007/s00170-012-3974-x.

[149] Veryzer R. Discontinuous Innovation and the New Product Development Process. Journal of Product Innovation Management. 1998;15(4):304–21. doi. 10.1016/S0737-6782(97)00105-7.

[150] Annacchino M. New Product Development: From Initial Idea to Product Management. Amsterdam: Elsevier; 2003.

[151] Holahan PJ, Sullivan ZZ, Markham SK. Product development as core competence: How formal product development practices differ for radical, more innovative, and incremental product innovations. Journal of Product Innovation Management. 2014;31(2):329–45. doi. 10.1111/jpim.12098.

[152] Clark KB, Wheelwright SC. Managing New Product and Process Development: Text and Cases. New York: Free Press; 1993.

[153] Keller RT. Technology-Information Processing Fit and the Performance of R&D Project Groups: A Test of Contingency Theory. Academy of Management Journal. 1994;37(1):167–79. doi. 10.2307/256775.

[154] Cardinal LB. Technological Innovation in the Pharmaceutical Industry: The Use of Organizational Control in Managing Research and Development. Organization Science. 2001;12(1):19–36. doi. 10.1287/orsc.12.1.19.10119.

[155] Griffin A, Price R, Vojak B, Hoffman N. Serial Innovators' processes: How they overcome barriers to creating radical innovations. Industrial Marketing Management. 2014;43(8):1362–71. doi. 10.1016/j.indmarman.2014.08.010.

[156] Reid SE, De Brentani U. The fuzzy front end of new product development for discontinuous innovations: A theoretical model. Journal of Product Innovation Management. 2004;21(2):170–84. doi. 10.1111/j.0737-6782.2004.00068.x.

[157] Hubka V. Principles of Engineering Design. London: Butterworth Scientific; 1982.

[158] Eder W, Hosnedl S. Introduction to Design Engineering: Systematic Creativity and Management. London: CRC Press; 2010.

[159] Ullman DG. The Mechanical Design Process. 4th ed. New York: McGraw-Hill; 2010.

[160] Cross N. Engineering design methods: Strategies for product design. 3rd ed. New York: John Wiley & Sons; 2000.

[161] Eggert RJ. Engineering Design. New Jersey: Pearson Prentice Hall; 2005.

[162] Ertas A, Jones JC. The Engineering Design Process. New York: John Wiley & Sons; 1993.

[163] Dieter GE, Schmidt LC. Engineering Design. 5th ed. New York: McGraw-Hill; 2013.

[164] Dym CL, Little P, Orwin EJ. Engineering Design: A Project-Based Introduction. 4th ed. Wiley; 2014.

[165] Haik Y, Shahin TM. Engineering Design Process. 2nd ed. Stamford, CT: Cengage Learning; 2011.

[166] Krumhauer P. Rechnerunterstützung für die Konzeptphase der Konstruktion [PhD Thesis]. [Berlin]: TU Berlin; 1974.

[167] Simon HA. The structure of ill structured problems. Artificial Intelligence. 1973;4(3–4):181–201. doi. 10.1016/0004-3702(73)90011-8.

[168] Restrepo J, Christiaans H. Problem structuring and information access in design. Journal of Design Research. 2004;4(2):218–36. doi. 10.1504/JDR.2004.009842.

[169] Vermaas PE. Design Theories, Models and Their Testing: On the Scientific Status of Design Research. In: Chakrabarti A, Blessing L, editors. An Anthology of Theories and Models of Design. London: Springer; 2014. p. 47–66. doi. 10.1007/978-1-4471-6338-1_2.

[170] Wynn DC, Eckert CM. Perspectives on iteration in design and development. Research in Engineering Design. 2017;28(2):153–84. doi. 10.1007/s00163-016-0226-3.

[171] Liikkanen LA, Perttula M. Exploring problem decomposition in conceptual design among novice designers. Design Studies. 2009;30(1):38–59. doi. 10.1016/j.destud.2008.07.003.

[172] Fiorineschi L, Rotini F, Rissone P. A new conceptual design approach for overcoming the flaws of functional decomposition and morphology. Journal of Engineering Design. 2016;27(7):438–68. doi. 10.1080/09544828.2016.1160275.

[173] Visser W. Design: one, but in different forms. Design Studies. 2009;30(3):187–223. doi. 10.1016/j.destud.2008.11.004.

[174] Dorst K, Cross N. Creativity in the design process: Co-evolution of problem-solution. Design Studies. 2001;22(5):425–37. doi. 10.1016/S0142-694X(01)00009-6.

[175] Eisenbart B, Gericke K, Blessing LTM. Taking a look at the utilisation of function models in interdisciplinary design: insights from ten engineering companies. Research in Engineering Design. 2017;28(3):299–331. doi. 10.1007/s00163-016-0242-3.

[176] Asimow M. Introduction to design. Englewood Cliffs, NJ: Prentice-Hall; 1962.

[177] Watts RD. The elements of design. In: Gregory SA, editor. The Design Method. Boston: Springer; 1966. p. 85–95. doi. 10.1007/978-1-4899-6331-4_11.

[178] Maher ML, Poon J, Boulanger S. Formalising Design Exploration as Co-Evolution. In: Gero JS, editor. Advances in Formal Design Methods for CAD. IFIP — The International Federation for Information Processing. Boston: Springer; 1996. p. 3–30. doi. 10.1007/978-0-387-34925-1_1.

[179] Kruger C, Cross N. Solution driven versus problem driven design: strategies and outcomes. Design Studies. 2006;27(5):527–48. doi. 10.1016/j.destud.2006.01.001.

[180] Frillici FS, Fiorineschi L, Cascini G. Linking TRIZ to Conceptual Design Engineering Approaches. Procedia Engineering. 2015;131:1031–40. doi. 10.1016/j.proeng.2015.12.421.

[181] Kumar A, Ganesh LS. Inter-individual knowledge transfer and performance in product development. Learning Organization. 2011;18(3):224–38. doi. 10.1108/09696471111123270.

[182] Ruiz PP, Maier AM. Towards describing co-design by the integration of engineering design and technology and innovation management literature. In: Hansen PK, Rasmussen J, Jřrgensen KA, Tollestrup C, editors. Proceedings of NordDesign 2012, the 9th NordDesign conference; Aarlborg University, Denmark, 22-24.08.2012. The Design Society; 2012.

[183] McMahon CA. Reflections on diversity in design research. Journal of Engineering Design. 2012;23(8):563–76. doi. 10.1080/09544828.2012.676634.

[184] McMahon CA. Observations on modes of incremental change in design. Journal of Engineering Design. 1994;5(3):195–209. doi. 10.1080/09544829408907883.

[185] Weber C. Modelling Products and Product Development Based on Characteristics and Properties. In: Chakrabarti A, Blessing L, editors. An Anthology of Theories and Models of Design. London; 2014. p. 327–52. doi. 10.1007/978-1-4471-6338-1_16.

[186] Andersson P. On robust design in the conceptual design phase: A qualitative approach. Journal of Engineering Design. 1997;8(1):75–89. doi. 10.1080/09544829708907953.

[187] Stacey M, Lauche K. Thinking and representing in design. In: Clarkson J, Eckert C, editors. Design Process Improvement. London: Springer; 2005. doi. 10.1007/978-1-84628-061-0_9.

[188] Vadde S, Allen J, Lucas T, Mistree F. On modeling design evolution along a design timeline. In: 5th Symposium on Multidisciplinary Analysis and Optimization; Panama City Beach, FL, USA, 07-09.09.1994. American Institute of Aeronautics and Astronautics; 1994. doi. 10.2514/6.1994-4313.

[189] Taura T. Motive of Design: Roles of Pre- and Post-design in Highly Advanced Products. In: Chakrabarti A, Blessing L, editors. An Anthology of Theories and Models of Design. London: Springer; 2014. p. 83–98. doi. 10.1007/978-1-4471-6338-1_4.

[190] Cabanes B, Galy P, Le Masson P, Weil B. Technical Staff Managementfor Radical Innovation in Science-based Organizations: a New Framework Based on Design Theory. In: R&D Management Conference; Cambridge, United Kingdom, 03-06.07.2016. 2016.

[191] Summers JD. Reasoning in Engineering Design. In: Proceedings of the 17th International Conference on Design Theory and Methodology; Long Beach, CA, USA, 24–28.09.2005. ASME; 2005. p. 329–40. doi. 10.1115/DETC2005-85334.

[192] Lu SCY, Liu A. Abductive reasoning for design synthesis. CIRP Annals. 2012;61(1):143–6. doi. 10.1016/j.cirp.2012.03.062.

[193] Hatchuel A, Weil B. A new approach of innovative design: An introduction to C-K theory. In: Proceedings of ICED 03, the 14th International Conference on Engineering Design; Stockholm, Sweden, 19-21.08.2003. 2003.

[194] Hatchuel A, Weil B. C-K design theory: an advanced formulation. Research in Engineering Design. 2009;19(4):181–92. doi. 10.1007/s00163-008-0043-4.

[195] Culley SJ. Suppliers in New Product Development: Their Information and Integration. Journal of Engineering Design. 1999;10(1):59–75. doi. 10.1080/095448299261425.

[196] Allwood CM, Kalén T. Usability in CAD-a psychological perspective. International Journal of Human Factors in Manufacturing. 1994;4(2):145–65. doi. 10.1002/hfm.4530040204.

[197] Black I, Nigel Shaw W. Organizational and managerial aspects of CAD in mechanical design. Design Studies. 1991;12(2):96–101. doi. 10.1016/0142-694X(91)90051-W.

[198] Rigger E, Vosgien T. Design automation state of practice - potential and opportunities. In: Marjanović D, Štorga M, Škec S, Bojčetić N, Pavković N, editors. Proceedings of the 15th International Design Conference DESIGN 2018; Dubrovnik, Croatia, 21-24.05.2018. Zagreb: The Design Society; 2018. p. 441–52. doi. 10.21278/idc.2018.0537.

[199] Reymen IMMJ, Hammer DK, Kroes PA, Van Aken JE, Dorst CH, Bax MFT, et al. A domain-independent descriptive design model and its application to structured reflection on design processes. Research in Engineering Design. 2006;16(4):147–73. doi. 10.1007/s00163-006-0011-9.

[200] Stompff G, Smulders F, Henze L. Surprises are the benefits: reframing in multidisciplinary design teams. Design Studies. 2016;47:187–214. doi. 10.1016/j.destud.2016.09.004.

[201] Wynn D, Clarkson J. Models of designing. In: Clarkson J, Eckert C, editors. Design Process Improvement. London: Springer; 2005. p. 34–59. doi. 10.1007/978-1-84628-061-0_2.

[202] Ensici A, Badke-Schaub P, Bayazit N, Lauche K. Used and rejected decisions in design teamwork. CoDesign. 2013;9(2):113–31. doi. 10.1080/15710882.2013.782411.

[203] Cardoso C, Badke-Schaub P, Eris O. Inflection moments in design discourse: How questions drive problem framing during idea generation. Design Studies. 2016;46:59–78. doi. 10.1016/j.destud.2016.07.002.

[204] Sung E, Kelley TR. Identifying design process patterns: a sequential analysis study of design thinking. International Journal of Technology and Design Education. 2019;29(2):283–302. doi. 10.1007/s10798-018-9448-1.

[205] Kan JWT, Gero JS, Tang HH. Measuring Cognitive Design Activity Changes during an Industry Team Brainstorming Session. In: Gero JS, editor. Design Computing and Cognition '10. Dordrecht: Springer; 2011. p. 621–40. doi. 10.1007/978-94-007-0510-4_33.

[206] Gero JS, Jiang H. Exploring the Design Cognition of Concept Design Reviews Using the FBS-Based Protocol Analysis. In: Adams R, Buzzanell P, Siddiqui J, editors. Analyzing Design Review Conversations. West Lafayette: Purdue University Press; 2015. p. 177–94. doi. 10.5703/1288284315931.

[207] Gero JS, Jiang H, Williams CB. Design cognition differences when using unstructured, partially structured, and structured concept generation creativity techniques. International Journal of Design Creativity and Innovation. 2013;1(4):196–214. doi. 10.1080/21650349.2013.801760.

[208] Eckert C, Clarkson J. The reality of design. In: Clarkson J, Eckert C, editors. Design Process Improvement. London: Springer; 2005. p. 1–29. doi. 10.1007/978-1-84628-061-0_1.

[209] Kannengiesser U, Gero JS. Is designing independent of domain? Comparing models of engineering, software and service design. Research in Engineering Design. 2015;26(3):253–75. doi. 10.1007/s00163-015-0195-y.

[210] Roozenburg NFM, Eekels J. Product design: fundementals and methods. 2nd ed. Chichester: Wiley; 1995.

[211] Gero JS. Design Prototypes: A Knowledge Representation Schema for Design. AI Magazine. 1990;11(4):26. doi. 10.1609/aimag.v11i4.854.

[212] Cascini G, Fantoni G, Montagna F. Situating needs and requirements in the FBS framework. Design Studies. 2013;34(5):636–62. doi. 10.1016/j.destud.2012.12.001.

[213] Liu A, Lu SCY. Alternation of analysis and synthesis for concept generation. CIRP Annals. 2014;63(1):177–80. doi. 10.1016/j.cirp.2014.03.094.

[214] Eckert CM, Stacey M, Wyatt D, Garthwaite P. Change as little as possible: creativity in design by modification. Journal of Engineering Design. 2012;23(4):337–60. doi. 10.1080/09544828.2011.639299.

[215] Jin Y, Chusilp P. Study of mental iteration in different design situations. Design Studies. 2006;27(1):25–55. doi. 10.1016/j.destud.2005.06.003.

[216] Khaidzir KAM, Lawson B. The cognitive construct of design conversation. Research in Engineering Design. 2013;24(4):331–47. doi. 10.1007/s00163-012-0147-8.

[217] Afacan Y, Demirkan H. An ontology-based universal design knowledge support system. Knowledge-Based Systems. 2011;24(4):530–41. doi. 10.1016/j.knosys.2011.01.002.

[218] Srinivasan V, Chakrabarti A. An Integrated Model of Designing. Journal of Computing and Information Science in Engineering. 2010;10(3):031013. doi. 10.1115/1.3467011.

[219] Aurisicchio M, Bracewell RH, Wallace KM. Characterising the information requests of aerospace engineering designers. Research in Engineering Design. 2013;24(1):43–63. doi. 10.1007/s00163-012-0136-y.

[220] Wong YL, Siu KWM. A model of creative design process for fostering creativity of students in design education. International Journal of Technology and Design Education. 2012;22(4):437–50. doi. 10.1007/s10798-011-9162-8.

[221] Mc Neill T, Gero JS, Warren J. Understanding conceptual electronic design using protocol analysis. Research in Engineering Design. 1998;10(3):129–40. doi. 10.1007/BF01607155.

[222] Casakin H, Badke-Schaub P. Sharedness of team mental models in the course of design-related interaction between architects and clients. Design Science. 2017;3(e14). doi. 10.1017/dsj.2017.15.

[223] Smithers T. Synthesis in Designing. In: Gero JS, editor. Artificial Intelligence in Design '02. Dordrecht: Springer; 2002. p. 3–24. doi. 10.1007/978-94-017-0795-4_1.

[224] McTeague C, Duffy A, Campbell G, Grealy M, Hay L, Pidgeon L, et al. An exploration of design synthesis. In: Maier A, Škec S, Kim H, Kokkolaras M, Oehmen J, Fadel G, et al., editors. Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 8: Human Behaviour in Design; Vancouver, Canada, 21-25.08.2017. The Design Society; 2017. p. 279–88.

[225] Sarkar P, Chakrabarti A. Ideas generated in conceptual design and their effects on creativity. Research in Engineering Design. 2014;25(3):185–201. doi. 10.1007/s00163-014-0173-9.

[226] Dorst K, Vermaas PE. John Gero's function-behaviour-structure model of designing: A critical analysis. Research in Engineering Design. 2005;16(1–2):17–26. doi. 10.1007/s00163-005-0058-z.

[227] Ball LJ, Onarheim B, Christensen BT. Design requirements, epistemic uncertainty and solution development strategies in software design. Design Studies. 2010;31(6):567–89. doi. 10.1016/j.destud.2010.09.003.

[228] Howard TJ, Dekoninck EA, Culley SJ. The use of creative stimuli at early stages of industrial product innovation. Research in Engineering Design. 2010;21(4):263–74. doi. 10.1007/s00163-010-0091-4.

[229] Srinivasan V, Chakrabarti A. Investigating novelty-outcome relationships in engineering design. Artificial Intelligence for Engineering Design, Analysis and Manufacturing. 2010;24(2):161–78. doi. 10.1017/S089006041000003X.

[230] Toh CA, Miller SR. How engineering teams select design concepts: A view through the lens of creativity. Design Studies. 2015;38:111–38. doi. 10.1016/j.destud.2015.03.001.

[231] Hatchuel A. Towards Design Theory and expandable rationality : The unfinished program of Herbert Simon . 1 From Decision making to Design theory : 2002;1–12.

[232] Maynard MT, Kennedy DM, Sommer SA. Team adaptation: A fifteen-year synthesis (1998–2013) and framework for how this literature needs to "adapt" going forward. European Journal of Work and Organizational Psychology. 2015;24(5):652–77. doi. 10.1080/1359432X.2014.1001376.

[233] Gonçalves M, Cardoso C, Badke-Schaub P. What inspires designers? Preferences on inspirational approaches during idea generation. Design Studies. 2014;35(1):29–53. doi. 10.1016/j.destud.2013.09.001.

[234] Vasconcelos LA, Crilly N. Inspiration and fixation: Questions, methods, findings, and challenges. Design Studies. 2016;42:1–32. doi. 10.1016/j.destud.2015.11.001.

[235] Petersson AM, Lundberg J. Developing an ideation method to be used in cross-functional inter-organizational teams by means of action design research. Research in Engineering Design. 2018;29(3):433–57. doi. 10.1007/s00163-018-0283-x.

[236] Nikander JB, Liikkanen LA, Laakso M. The preference effect in design concept evaluation. Design Studies. 2014;35(5):473–99. doi. 10.1016/j.destud.2014.02.006.

[237] Toh CA, Miller SR. Choosing creativity: the role of individual risk and ambiguity aversion on creative concept selection in engineering design. Research in Engineering Design. 2016;27(3):195–219. doi. 10.1007/s00163-015-0212-1.

[238] Toh CA, Miller SR, Okudan Kremer GE. The Impact of Team-Based Product Dissection on Design Novelty. Journal of Mechanical Design. 2014;136(4):041004. doi. 10.1115/1.4026151.

[239] López-Mesa B, Bylund N. A study of the use of concept selection methods from inside a company. Research in Engineering Design. 2011;22(1):7–27. doi. 10.1007/s00163-010-0093-2.

[240] Sarkar P, Chakrabarti A. A Model for the Process of Idea Generation. The Design Journal. 2017;20(2):239–57. doi. 10.1080/14606925.2017.1272244.

[241] Liikkanen LA, Perttula M. Inspiring design idea generation: insights from a memory-search perspective. Journal of Engineering Design. 2010;21(5):545–60. doi. 10.1080/09544820802353297.

[242] López-Mesa B, Mulet E, Vidal R, Thompson G. Effects of additional stimuli on idea-finding in design teams. Journal of Engineering Design. 2011;22(1):31–54. doi. 10.1080/09544820902911366.

[243] Hatcher G, Ion W, Maclachlan R, Marlow M, Simpson B, Wilson N, et al. Using linkography to compare creative methods for group ideation. Design Studies. 2018;58:127–52. doi. 10.1016/j.destud.2018.05.002.

[244] Adams RS, Cardella M, Purzer Ş. Analyzing design review conversations: Connecting design knowing, being and coaching. Design Studies. 2016;45:1–8. doi. 10.1016/j.destud.2016.03.001.

[245] McDonnell J. Descriptive models for interpreting design. Design Studies. 1997;18(4):457–73. doi. http://dx.doi.org/10.1016/S0142-694X(97)00012-4.

[246] Harvey S, Kou CY. Collective Engagement in Creative Tasks: The Role of Evaluation in the Creative Process in Groups. Administrative Science Quarterly. 2013;58(3):346–86. doi. 10.1177/0001839213498591.

[247] Yilmaz S, Daly SR. Feedback in concept development: Comparing design disciplines. Design Studies. 2016;45:137–58. doi. 10.1016/j.destud.2015.12.008.

[248] Goldschmidt G. Linkographic Evidence for Concurrent Divergent and Convergent Thinking in Creative Design. Creativity Research Journal. 2016;28(2):115–22. doi. 10.1080/10400419.2016.1162497.

[249] Milne AJ. Analysing the Activity of Multidisciplinary Teams in the Early Stages of Conceptual Design: Method and Measures. In: Scrivener SAR, Ball LJ, Woodcock A, editors. Collaborative Design. London: Springer; 2000. p. 289–97. doi. 10.1007/978-1-4471-0779-8_28.

[250] Atman CJ, Adams RS, Cardella ME, Turns J, Mosborg S, Saleem J. Engineering Design Processes: A Comparison of Students and Expert Practitioners. Journal of Engineering Education. 2007;96(4):359–79. doi. 10.1002/j.2168-9830.2007.tb00945.x.

[251] Ullman DG, Dietterich TG, Stauffer L a. A model of the mechanical design process based on empirical data. Artificial Intelligence for Engineering, Design, Analysis and Manufacturing. 1988;2(01):33. doi. 10.1017/S0890060400000536.

[252] Goel V, Pirolli P. The structure of design problem spaces. Cognitive science. 1992;16(3):395–429. doi. 10.1207/s15516709cog1603_3.

[253] Le Masson P, Weil B, Hatchuel A. Design Theory. Cham: Springer; 2017. doi. 10.1007/978-3-319-50277-9.

[254] Liu YC, Bligh T, Chakrabarti A. Towards an "ideal" approach for concept generation. Design Studies. 2003;24(4):341–55. doi. 10.1016/S0142-694X(03)00003-6.

[255] Robinson MA. Quantitative research principles and methods for human-focused research in engineering design. In: Cash P, Stanković T, Štorga M, editors. Experimental Design Research: Approaches, Perspectives, Applications. Cham: Springer; 2016. p. 41–64. doi. 10.1007/978-3-319-33781-4_3.

[256] Perry GT, Krippendorff K. On the reliability of identifying design moves in protocol analysis. Design Studies. 2013;34(5):612–35. doi. 10.1016/j.destud.2013.02.001.

[257] Gagniuc PA. Markov Chains: From Theory to Implementation and Experimentation. Hoboken, NJ: Wiley; 2017. 256 p.

[258] Yammiyavar P, Clemmensen T, Kumar J. Influence of Cultural Background on Non-verbal Communication in a Usability Testing Situation. International Journal of Design. 2008;2(2):31–40.

[259] Cash P, Maier A. Prototyping with your hands: the many roles of gesture in the communication of design concepts. Journal of Engineering Design. 2016;27(1–3):118–45. doi. 10.1080/09544828.2015.1126702.

[260] Eder WE. Developments in Education for Engineering Design: Some Results of 15 Years of Workshop Design-Konstruktion Activity in the Context of Design Research. Journal of Engineering Design. 1994;5(2):135–44. doi. 10.1080/09544829408907879.

[261] Cash PJ, Hicks BJ, Culley SJ. A comparison of designer activity using core design situations in the laboratory and practice. Design Studies. 2013;34(5):575–611. doi. 10.1016/j.destud.2013.03.002.

[262] Bender B. Task design and task analysis for empirical studies into design activity. Journal of Engineering Design. 2003;14(4):399–408. doi. 10.1080/09544820310001606894.

[263] Cash PJ. Characterising the Relationship Between Practice and Laboratory-based Studies of Designers for Critical Design Situations [PhD Thesis]. [Bath]: University of Bath; 2012.

[264] Max Planck Institute for Psycholinguistics. ELAN. 2019. Available from: https://tla.mpi.nl/tools/tla-tools/elan/ [cited 2019 Apr 3];

[265] Klonek FE, Quera V, Burba M, Kauffeld S. Group interactions and time: Using sequential analysis to study group dynamics in project meetings. Group Dynamics: Theory, Research, and Practice. 2016;20(3):209–22. doi. 10.1037/gdn0000052.

[266] Snider C, Dekoninck E, Culley S. Beyond the concept: characterisations of later-stage creative behaviour in design. Research in Engineering Design. 2016;27(3):265–89. doi. 10.1007/s00163-016-0218-3.

[267] Quera V, Bakeman R, Gnisci A. Observer agreement for event sequences: Methods and software for sequence alignment and reliability estimates. Behavior Research Methods. 2007;39(1):39–49. doi. 10.3758/BF03192842.

[268] Nguyen P, Nguyen TA, Zeng Y. Empirical approaches to quantifying effort, fatigue and concentration in the conceptual design process. Research in Engineering Design. 2018;29(3):393–409. doi. 10.1007/s00163-017-0273-4.

[269] Pourmohamadi M, Gero JS. LINKOgrapher: An Analysis Tool to Study Design Protocols Based on FBS Coding. In: Culley SJ, Hicks BJ, McAloone TC, Howard TJ, Reich Y, editors. Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 2: Design Theory and Research Methodology; Lyngby/Copenhagen, Denmark, 15-19.08.2011. The Design Society; 2011. p. 294–303.

[270] Cash P, Stanković T, Štorga M. Using visual information analysis to explore complex patterns in the activity of designers. Design Studies. 2014;35(1):1–28. doi. 10.1016/j.destud.2013.06.001.

[271] Lapp S. Designing Like a Human: Simulating Cognitive Style in Teamwork with an Agent-Based Model [Master Thesis]. The Pennsylvania State University; 2019. doi. 10.31237/osf.io/cdsyr.

[272] Teetor P. R Cookbook. Sebastopol, CA: O'Reilly; 2011.

[273] Blizzard J, Klotz L, Potvin G, Hazari Z, Cribbs J, Godwin A. Using survey questions to identify and learn more about those who exhibit design thinking traits. Design Studies. 2015;38:92–110. doi. 10.1016/j.destud.2015.02.002.

[274] Chan KY, Kwong CK, Dillon TS, Fung KY. An intelligent fuzzy regression approach for affective product design that captures nonlinearity and fuzziness. Journal of Engineering Design. 2011;22(8):523–42. doi. 10.1080/09544820903550924.

[275] The R Foundation. The R Project for Statistical Computing. 2019. Available from: https://www.r-project.org/ [cited 2019 Apr 6];

[276] Kannengiesser U, Gero JS. Can Pahl and Beitz' systematic approach be a predictive model of designing? Design Science. 2017;3:e24. doi. 10.1017/dsj.2017.24.

[277] Smith RP, Tjandra P. Experimental observation of iteration in engineering design. Research in Engineering Design. 1998;10(2):107–17. doi. 10.1007/BF01616691.

[278] Chakrabarti A, Morgenstern S, Knaab H. Identification and application of requirements and their impact on the design process: A protocol study. Research in Engineering Design. 2004;15(1):22–39. doi. 10.1007/s00163-003-0033-5.

[279] Casakin H, Badke-Schaub P. Mental Models and Creativity in Engineering and Architectural Design Teams. In: Gero J, Hanna S, editors. Design Computing and Cognition '14. Cham: Springer; 2015. p. 155–71. doi. 10.1007/978-3-319-14956-1_9.

[280] Atman CJ, Chimka JR, Bursic KM, Nachtmann HL. A comparison of freshman and senior engineering design processes. Design Studies. 1999;20(2):131–52. doi. 10.1016/S0142-694X(98)00031-3.

[281] Cross N. Understanding Design Cognition. In: Designerly Ways of Knowing. London: Springer; 2006. p. 77–93. doi. 10.1007/1-84628-301-9_6.

[282] Smith J, Clarkson PJ. Design concept modelling to improve reliability. Journal of Engineering Design. 2005;16(5):473–92. doi. 10.1080/09544820500273268.

[283] Fricke G. Successful approaches in dealing with differently precise design problems. Design Studies. 1999;20(5):417–29. doi. 10.1016/S0142-694X(99)00018-6.

[284] Guindon R. Designing the Design Process: Exploiting Opportunistic Thoughts. Human–Computer Interaction. 1990;5(2–3):305–44. doi. 10.1080/07370024.1990.9667157.

[285] Purcell AT, Gero JS, Edwards H, McNeill T. The data in design protocols: The issue of data coding, data analysis in the development of models of the design process. In: Cross N, Christiaans H, Dorst K, editors. Analysing Design Activity. Chichester, NY: Wiley; 1996. p. 225–52.

[286] Tversky B, Chou JY. Creativity: Depth and Breadth. In: Taura T, Nagai Y, editors. Design Creativity 2010. London: Springer; 2011. p. 209–14. doi. 10.1007/978-0-85729-224-7_27.

[287] López-Mesa B, Thompson G. On the significance of cognitive style and the selection of appropriate design methods. Journal of Engineering Design. 2006;17(4):371–86. doi. 10.1080/09544820500274100.

[288] Martinec T, Horvat N, Škec S, Štorga M. Verbal engagement in teams solving a conceptual design task. In: Marjanović D, Štorga M, Škec S, Bojčetić N, Pavković N, editors. Proceedings of the 15th International Design Conference DESIGN 2018; Dubrovnik, Croatia, 21-24.05.2018. The Design Society; 2018. p. 2075–86. doi. 10.21278/idc.2018.0540.

BIOGRAPHY

Tomislav Martinec was born in Čakovec, Croatia, in 1989. After graduating from gymnasium, he enrolled in the study of Mechanical Engineering at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb (UNIZAG-FSB) in 2008. In 2012, he gained a bachelor's degree and a year later a master's degree in mechanical engineering, specialising in Product Design and Development. During his studies, he was awarded the "Davorin Bazjanac Award" and the "Faculty Medal".

After graduation, he started working as a Teaching Assistant at the Chair of Design and Product Development at UNIZAG-FSB. His primary field of research and scientific focus in the last years has included information traceability and visualisation in product development, management of relations between engineering objects and teamwork in the conceptual design stage. He has co-authored 3 journal papers and 12 conference papers.

He currently participates in Croatian Science Foundation (CSF) project "Team Adaptability for Innovation-Oriented Product Development – TAIDE". From 2014 to 2018 he was part of the CSF project "Models and Methods of Innovation Management in Complex Engineering Systems Development – MInMED". From 2015 to 2017 he participated in Erasmus+ project "Networked Activities for Realisation of Innovative Products – NARIP".

He visited Luleå Technical University several times throughout his doctoral research. In addition, he enrolled in summer schools organised by the Technical University of Denmark, Otto von Guericke University in Magdeburg and University of Malta.

He is a member of the Design Society. Since 2014 he actively participates in the organisation of the DESIGN conference, a biennial event that regularly attracts more than 250 experts from more than 30 countries around the world.

ŽIVOTOPIS

Tomislav Martinec je rođen u Čakovcu 1989. godine. Po završetku Prve gimnazije u Varaždinu 2008. godine upisuje Studij strojarstva na Fakultetu strojarstva i brodogradnje, Sveučilišta u Zagrebu (UNIZAG-FSB). Diplomu prvostupnika inženjerstva strojarstva stekao je 2012. godine, a godinu dana kasnije stekao je zvanje magistra inženjera strojarstva na usmjerenju Konstruiranje i razvoj proizvoda. Za vrijeme studija nagrađen je priznanjima "Davorin Bazjanac" i "Medalja Fakulteta".

Od 2014. godine zaposlen je kao asistent na Katedri za konstruiranje i razvoj proizvoda. Primarna područja istraživanja proteklih godina uključuju sljedivost i vizualizaciju informacija u razvoju proizvoda, upravljanje relacijama između inženjerskih objekata te timski rad u fazi koncipiranja proizvoda. Koautor je 3 rada u časopisu i 12 radova na međunarodnim konferencijama.

Sudjeluje kao suradnik na projektu Hrvatske zaklade za znanost naziva "Timska adaptabilnost u razvoju inovativnih proizvoda – TAIDE". Od 2014. do 2018. godine sudjelovao je na HRZZ projektu "Modeli i metode upravljanja inovacijama u razvoju kompleksnih inženjerskih sustava – MInMED". Od 2015. do 2017. godine sudjelovao je na Erasmus+ projektu "Networked Activities for Realisation of Innovative Products – NARIP".

Tijekom istraživanja nekoliko puta je boravio na Tehničkom sveučilištu Luleå, te sudjelovao na međunarodnim ljetnim školama u organizaciji Danskog tehničkog sveučilišta, Sveučilišta Otto von Guericke u Magdeburgu te Sveučilišta na Malti.

Član je zajednice Design Society. Od 2014. godine aktivno sudjeluje u organizaciji međunarodne DESIGN konferencije, koja svake dvije godine privlači više od 350 stručnjaka iz više od 30 zemalja iz cijelog svijeta.

BIBLIOGRAPHY

Journal papers:

Martinec, T., Škec, S., Horvat, N., Štorga, M. (2019). A state-transition model of team conceptual design activity. *Research in Engineering Design*, 30(1), 103-132. https://doi.org/10.1007/s00163-018-00305-1

Martinec, T., Škec, S., Savšek, T., Perišić, M. M. (2017). Work sampling for the production development: A case study of a supplier in European automotive industry. *Advances in Production Engineering & Management*, 12(4), 375-387. https://doi.org/10.14743/apem2017.4.265

Pavković, N., Martinec, T., Marjanović, D. (2018). Consolidation of Methods for Visualization and Management of Engineering Design Data Sets. *Tehnički vjesnik*, 25(1), 26-39. https://doi.org/10.17559/TV-20160707093053

Selected conference papers:

Martinec, T., Škec, S., Šklebar, J., Štorga, M. (2019). Applying Engineering Design Ontology for Content Analysis of Team Conceptual Design Activity. In: Proceedings of the 22nd International Conference on Engineering Design (ICED 19), Delft, The Netherlands, 05-08.08.2019. (pp. 2467-2476) https://doi.org/10.1017/dsi.2019.253

Nikolić, M., Škec, S., Martinec, T., Horvat, N. (2019). The Role of Sketching Activities and Outcomes in Conceptual Design Phase. In: Proceedings of the 22nd International Conference on Engineering Design (ICED 19), Delft, The Netherlands, 05-08.08.2019. (pp. 399-408). https://doi.org/10.1017/dsi.2019.43

Martinec, T., Horvat, N., Škec, S., Štorga, M. (2018). Verbal Engagement in Teams Solving a Conceptual Design Task. In: *Proceedings of the 15th International Design Conference (DESIGN 2018)*, Dubrovnik, Croatia, 21-24.05.2018. (pp. 2075-2086). https://doi.org/10.21278/idc.2018.0540

Martinec, T., Škec, S., Štorga, M. (2017). Exploring the decomposition of team design activity. In *Proceedings of the 21st International Conference on Engineering Design (ICED 17)*, Vancouver, Canada, 21-25.08. 2017. (pp. 229-238).

Perišić, M. M., Martinec, T., Štorga, M., Kanduč, T. (2016). Agent-based simulation framework to support management of teams performing development activities. In *Proceedings of the 14th International Design Conference (DESIGN 2016),* Cavtat, Croatia, 16-19.05.2018. (pp. 1925-1936).

Pavković, N., Martinec, T., Rohde, D., Šikic, B. (2015). Management and Visualization of Relationships Between Engineering Objects. In *Proceedings of the 20th International Conference on Engineering Design (ICED 15),* Milan, Italy, 27-30.07.2015. (pp. 177-186).

Martinec, T., Pavković, N. (2014). Visualization of information traceability in product development. In *Proceedings of the 13th International Design Conference (DESIGN 2014),* Cavtat, Croatia, 19-22.05.2014. (pp. 1831-1842).