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OF TECHNOLOGY

Doctoral Thesis in Machine Design

Mechatronic Metaphors

An Embodied Realist Framework of Complexity and Expertise in Mechatronic Project Work

ELIAS FLENING

Stockholm, Sweden 2023

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To my wife, Suzanne.

(Doo~)

Acknowledgments

I was profoundly curious and not a little confused about a great many things when setting out on this doctoral journey in 2016. In finishing it, I happily find myself with more of both. Gratitude is one of the most productive and prosocial mental states across the board. I have heaps of it here at the end.

I would like to thank my main supervisor Martin Grimheden for not only his care and engagement in my development as a researcher during my PhD, but also during my bachelor and master years: For fifteen years and over my three cycles of studies you have taken me into our *mechatronics*, both the field of thought and its physical place here at KTH.

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However, none of this would probably have happened if it was not for the initial encouragement that Cali Nuur gave me over fifteen years ago. You showed me how fascinatingly odd acts of organizing work can be, kindling my now burning curiosity in its mundane absurdity, and you were the first to support my budding interest in its research. It has stayed with me throughout. Thank you for that.

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Abstract

Mechatronic development project work contains high levels of complexity and demands expertise in equal measure. In the context of global declining productivity gains from engineering work and persistent wicked problems in mechatronic system development – with long-reported challenges like a lack of common system understanding, absence of a common language for concepts, and disparate mental models – understanding real-world perceptions of complexity and competence becomes critical.

The aim is to address the underlying concern in these challenges (i.e., declining productivity) by problematizing their inherent assumptions of unity as a solution-heuristic. Instead, taking an organizing perspective on these challenges based on Project Studies, alternative assumptions are offered which hold these same underlying concerns. The thesis then explores how perceptions of expertise (RQ1.1) and complexity (RQ1.2) are generated in the lived experience of mechatronic project work, both at the individual and team levels. The thesis also asks how expertise and complexity are experienced in actual mechatronic project work: what makes their experiential relation (RQ2)?

To answer the research questions, an abductive approach using mixed methods is taken over the five included publications to iteratively produce a framework. Using both quantitative (surveys) and qualitative (interviews & observations), the framework is constructed based on two theories: Legitimation Code Theory (LCT) and the Integrated Theory of Primary Metaphor (ITPM). LCT is used to explain how knowledge relate to expertise, and how expertise connects to complexity. ITPM is used to explain how the micro-level dynamics of complexity-perception in individuals are determined by embodied conceptual metaphor. Which is a mostly unconscious cognitive process whereby concrete physical sensorimotor sensations are conflated with basic conceptual categories (e.g., conflating warmth with affection) called primary metaphors. These primary metaphors integrate into single embodied conceptual metaphors which directly represents highly abstract ideas such as complexity and expertise.

The thesis found the following: that perceptions of expertise are generated based on a three-part model of expertise: the model states that expertise constitutes an ability to *enact* technical knowledge, through *collaborating* in social networks of professional actors, by continually *recognizing* what the present legitimate basis for practice is. Complexity in turn is experienced as that which is perceived as *important* and *difficult*, through several dimensions of complexity and driven by specific factors. With *size* being an empirically

observed underlying logic for that perception. Answering RQ2 using ITPM, the framework show that complexity and competence, two abstract concepts, are experienced directly through sensorimotor perceptions, physical experiences, in everyday mechatronic project work. The experiential relation between these two abstract concepts and direct physical experience is constituted by embodied conceptual metaphor, out of which the thesis found one novel metaphor in the case study data.

The thesis' findings, synthesised in the framework, affords a granular and realist view of the identified mechatronic challenges concerned with *common language* and *understanding*. This view free both mechatronic project team-members from the assumption of *unity* in a way that does not through throw the baby out with the bathwater: By removing the expectation and valuation of unity as naturalized without throwing out efforts to create consensus and move the project forward. A more realistic and pragmatist stance which realizes and makes non-personal the mechanics of competence and complexity serves to open up for *free discussion* (one of the four core mechatronic challenges). The framework affords a context-sensitive model for promoting own understanding of the internal mechanisms in one's mind *and other's minds*. Essentially serving the same type of function as the V-model: a "*reminder model that guide us to less perilous paths when developing solutions to problems*" (Mooz & Forsberg, 2006, p. 1368).

All of this, instead of yet another attempt at a unified holistic system model based on non-real platonic ideals.

Sammanfattning

Utvecklingsprojekt inom mekatronik innehåller höga nivåer av komplexitet och kräver expertis i samma utsträckning för att hantera denna. I och med globalt minskande produktivitetsvinster från ingenjörsarbete samt "outtrassliga" (*wicked)* problem i utvecklingen av mekatroniska system – med sedan länge rapporterade utmaningar så som brist på gemensam systemförståelse, avsaknad av gemensamt språk för koncept, och disparata mentala modeller – så blir det kritiskt att förstå de faktiskt gällande uppfattningar av komplexitet och kompetens inom utvecklingsprojekt.

Syftet är att ta itu med den underliggande angelägenheten i dessa utmaningar (dvs. minskande produktivitet) genom att problematisera dess inneboende antaganden om enhetlighet som en lösnings-heuristik. Med ett organisatoriskt perspektiv på dessa utmaningar baserat på projektstudier erbjuds i stället alternativa antaganden, vilka behåller samma underliggande angelägenhet. Denna avhandling utforskar således hur uppfattningar omkring expertis (RQ1.1) och komplexitet (RQ1.2) genereras i upplevelsen av mekatroniskt projektarbete, både på individ- och teamnivåer. Avhandlingen frågar även hur expertis och komplexitet upplevs i faktiskt mekatroniskt projektarbete: vad består den upplevda relationen mellan expertis och komplexitet av (RQ2)?

För att svara på forskningsfrågorna används ett abduktivt tillvägagångssätt genom blandade metoder, över de fem sammanlagda publikationerna, för att iterativt framställa ett ramverk. Detta gör avhandlingen genom att använda både kvantitativa (enkätundersökning) och kvalitativa (intervjuer & observationer) metoder, vilka bygger ramverket baserat på två teorier: *Legitimation Code Theory* (LCT) och *Integrated Theory of Primary Metaphor* (ITPM). LCT används för att förklara hur kunskap relaterar till expertis, och hur expertis kopplas till komplexitet. ITPM används för att förklara hur mikronivå-dynamiken i individuella uppfattningar av komplexitet bestäms av förkroppsligade konceptmetaforer. Sådana kommer ut ur en mestadels omedveten kognitiv process där konkreta fysiska sensoriska sensationer sammanblandas med grundläggande konceptkategorier (t.ex. hur vi blandar fysiska sensationer av *värme* med grundkonceptet *tillgivenhet*). Denna sammanblandning kallade primärmetaforer. Sådana primärmetaforer kombineras till så kallade konceptmetaforer, vilka direkt representerar abstrakta icke-fysiska idéer såsom *komplexitet* och *expertis*. På detta sätt finner abstrakta idéer en indirekt koppling till det fysiska genom att de representeras i våra hjärnor av konceptmetaforer vilka består av flera primärmetaforer som sammanblandar sensoriska upplevelser med grundkoncept.

Avhandlingen fann följande: att uppfattningar om expertis genereras baserat på en tredelad modell av expertis. Denna modell förklarar att expertis utgör en förmåga att använda egen *teknisk kunskap*, genom att *samarbeta i sociala nätverk* av professionella aktörer, genom att kontinuerligt förstå vad som är den *nuvarande legitima grunden* för praktik (praxis). Avhandlingen fann också att komplexitet upplevs i sin tur som det som uppfattas som både *viktigt* och *svårt*, genom flera dimensioner av komplexitet och drivet av specifika faktorer, med storlek som en empiriskt observerad underliggande logik för komplexitet-uppfattning. Genom att besvara RQ2 med hjälp av ITPM, visar ramverket att komplexitet och kompetens, två abstrakta koncept, upplevs direkt genom sensomotoriska uppfattningar, fysiska erfarenheter, i det mekatroniska projektarbetets vardag. Den upplevda relationen mellan dessa två abstrakta koncept och direkt fysisk upplevelse utgörs av kroppsliga konceptmetaforer, av vilka avhandlingen fann en ny metafor i fallstudie-data.

Avhandlingens fynd som syntetiserats i ramverket ger en detaljerad och realist-orienterad bild av de identifierade mekatroniska utmaningarna, vilka berör gemensamt språk och förståelse. Denna syn befriar både mekatroniska projektteam-medlemmar från antagandet om *enhetlighet* på ett sätt som inte kastar ut barnet med badvattnet: Genom att ta bort förväntan av *enhetlighet* som naturligt utan att kasta ut verkliga ansträngningar för att skapa konsensus och driva projektet framåt. En mer realistisk och pragmatisk hållning som förverkligar och avpersonifierar kompetens och komplexitet öppnar upp för fri diskussion (en av de fyra kärnutmaningarna inom mekatronik). Ramverket ger en kontextkänslig modell för att främja egen förståelse av ens interna mekanismerna i det egna samt även *andras sinnen*. I grunden tjänar ramverket samma typ av funktion som V-modellen: en ”påminnelsemodell som leder oss till mindre riskfyllda vägar när vi utvecklar lösningar på problem” (Mooz & Forsberg, 2006, s. 1368).

Allt detta i stället för ännu ett försök till en enhetlig och total systemmodell baserad på icke-realistiska platoniska ideal.

Disclaimer

The fifth and final article

Flening, E., Jerbrant, A., & Edin Grimheden, M. (in press) EXPERIENCING PROJECT COMPLEXITY THROUGH PRIMARY METAPHORS IN MULTI-DISCIPLINARY ENGINEERING DEVELOPMENT PROJECTS

has been rejected by the International Journal of Managing Projects in Business and therefore is in the process of submission to another journal.

LIST OF INCLUDED PUBLICATIONS

1. Flening, E., & Jerbrant, A. (2018). *Worlds Apart and Close Together: Relating mechatronics and project management research*. Conference paper presented at the 2018 International Design Conference, DESIGN 2018.
   Anna wrote section 3 on Project Management, Elias wrote the rest. Both reviewed the whole work.

2. Flening, E., & Grimheden, M. (2018). *MANY MECHATRONICS : A discursive model of Mechatronics ' definitions*. Conference paper presented at MECHATRONICS 2018 - Reinventing Mechatronics, Glasgow, UK.
   Elias wrote the article and both reviewed the whole work.

3. Grimheden, M., & Flening, E. (2019). *50 years of mechatronics - What is next?* Conference paper presented at the 20th International Conference on Research and Education in Mechatronics, REM 2019.
   Elias wrote the Literature review, Methodology, Results and the first section (A) of the Discussion. Martin and Elias wrote the Introduction. Martin wrote the final two sections of the Discussion. Both reviewed the whole work. Elias collected the data.

4. Flening, E., Asplund, F., & Edin Grimheden, M. (2021). Measuring professional skills misalignment based on early-career engineers' perceptions of engineering expertise. *European Journal of Engineering Education, 47*(1), 117-143. doi:10.1080/03043797.2021.1967883.
   Elias wrote the article and all three reviewed the whole work. Elias collected the data. Fredrik and Martin provided feedback on data collection.

5. Flening, E., Jerbrant, A., & Edin Grimheden, M. (in press) EXPERIENCING PROJECT COMPLEXITY THROUGH PRIMARY METAPHORS IN MULTI-DISCIPLINARY ENGINEERING DEVELOPMENT PROJECTS. Submitted.
   Elias and Anna wrote section 2.3 together. Elias wrote the rest. Anna reviewed and edited the whole work. Martin reviewed the whole work. Elias collected the data. Anna and Martin provided feedback on data collection.

LIST OF ADDITIONAL PUBLICATIONS

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Grimheden, M., & Flening, E. (2022). Developing Education in Mechatronics to Support the Challenges for Evolution, Development, and Sustainability. *In EcoMechatronics (1st ed.).*doi:10.1007/978-3-031-07555-1_17

Abbreviations and explanation of terms

- **Complexity:** A holistic interpretation of perceived difficulties in relation to a system or process,
  AND/OR
- A multi-dimensional system property, often connected to the size of the systems internal structure and that structures interconnectedness and diversity. Frameworks and typologies vary on fundamental aspects, such as whether to include uncertainty/randomness and to what extent and form that social phenomena are included.

- **Expertise:** ability to enact technical knowledge through collaborating in professional social networks, which is enabled by continually recognizing the current legitimate basis for practice.

- **Competence:** used interchangeably with Expertise.

- **Embodied Realism:** Abstract concepts, ideas, and thoughts are body-based: it is "*the view that the locus of experience, meaning, and thought is the ongoing series of embodied organism–environment interactions that constitute our understanding of the world.*" (Johnson & Lakoff, 2002, p. 249). Johnson and Lakoff (2002) affords an excellent account of this ontological stance and its relation to conceptual metaphor and is therefore highly recommend reading.

- **Perception/perceiving:** A cognitive process of the body integrating sense-data.

- **Metaphor:** A statement relating a source concept to a target concept.

- **Primary metaphor:** A Cognitive process relating a sensorimotor source domain and a target domain.

- **Conceptual metaphor:** A Cognitive process combining several primary metaphors to represent increasingly complex concepts and ideas.

- ***ITPM*:** Integrated Theory of Primary Metaphor. It explains the process of how primary metaphor is instantiated neurally in the brain how several primary metaphors constitute conceptual metaphors, which represents abstract concepts and thought.

- **Interoception:** Process of perceiving stimuli arising within the body.
- **Project:** a logic for organizing temporary goal-oriented efforts.
- **Project work:** an actual practice of carrying out **project** tasks.
- ***PM*:** Project Management – the planning and control of **project work** *or* a field of study thereof.
- **Project Studies:** sub-type of ***PM*** focussing less on traditional notions of planning and control and more on context-sensitive lived experience of specific instances of **project work**.
- ***CPS***: Cyber-physical Systems are engineered systems that integrate algorithms and physical components to interact with the environment.
- ***SE***: Systems Engineering is a multidisciplinary field of engineering which uses *systems thinking* to design, implement, and manage complex systems over their life cycles to ensure they meet intended purposes and requirements.
- ***MBSE***: Model-based Systems Engineering is a SE methodology that uses modelling as the core for system requirements, description, design, analysis, verification, and validation.

CONTENTS

1 Introduction ... 1

1.1 Doing mechatronics: setting the scene ... 1

1.2 Historical and contemporary mechatronics ... 2

1.2.1 Four decades of evolving uniqueness of mechatronic ... 2

1.2.2 Contemporary framing of mechatronics ... 4

1.2.3 How Mechatronics perceives its own challenges ... 5

1.3 Project organizing ... 7

1.4 Thesis purpose and research questions ... 8

1.5 Thesis structure ... 11

2 Theoretical frame ... 12

2.1 Complexity ... 12

2.2 Engineering expertise ... 13

2.3 The Integrated Theory of Primary Metaphor ... 13

2.3.1 Bidirectional activation ... 14

2.3.2 Why use metaphor to understand mechatronic project work? ... 15

3 Research design ... 17

3.1 Research process: A narrative account of methodological choices ... 17

3.2 Delimitations and roads not travelled ... 21

3.3 Data collection and analysis ... 22

3.4 Criteria for assessing thesis trustworthiness ... 23

4 Publication summary ... 25

4.1 Reading guide ... 25

4.2 Paper 1 ... 26

4.3 Paper 2 ... 27

4.4 Paper 3 28
4.5 Paper 4 30
4.6 Paper 5 32
5 Synthesis of results 33
5.1 Motivating the framework 33
5.2 Constructing the framework base 34
5.2.1 A *Grand* and *loosely-coupled* discursive stance 35
5.2.2 A Type 2 project organizing focus 38
5.3 Complexity and Expertise 39
5.3.1 Expertise 40
5.3.2 Complexity 41
5.4 Conceptual metaphor 44
5.5 The full framework 47
5.5.1 Metaphors instantiates expertise-complexity relations 50
5.5.2 Constituting the experiential relation: answering RQ2 51
5.5.3 Alternative explanations of the expertise-complexity relation 52
6 Conclusion 54
6.1 Conclusion 54
6.2 limitations 55
6.3 implications and contributions 56
6.4 Future Research 58
7 References 59

LIST OF FIGURES

Figure 1: Thesis structure overview 11

Figure 2: the thesis' abductive reasoning structure 20

Figure 3: A discursive view of Mechatronics as a foundation for the framework....... 37

Figure 4: The inclusive and overlapping concept models enter the framework's positional base 38

Figure 5: Expertise enters the framework 40

Figure 6: Perceived complexity enters the framework 43

Figure 7: How physical experience form abstract concepts (with example: heat to motherly love) 44

Figure 8: ITPM enters the framework 46

Figure 9: the full framework 49

A note on paragraph-structure

Each paragraph is initialized with a bold topic sentence such as this one. The following sentences are formatted as body text. The reason is to focus the reading of the text on the logic of each paragraph carrying one argument or (main) point as a whole which the first topic sentence in bold delivers. The remainder of the paragraph qualifies, extends, exemplifies, bounds, or connects its argument to the rest of the text. Commonly to the immediately preceding paragraph. The end often serves to logically connect to the following paragraph's topic sentence. This point is important to explicate for the reader because it is intended to serve as a kind of micro-heading that summarizes arguments into block-pieces.

1 INTRODUCTION

1.1 DOING MECHATRONICS: SETTING THE SCENE

The execution of physically integrated engineering development projects has been the hallmark of the nineteenth century. Delivering new systems, increased system precision, and extending functionality has over time seen mounting need for disciplinary integration over fields of engineering. For most of this past century such delivery has used projects as a work-form to organize, plan and direct them (Lenfle & Loch, 2011). The practical proof of that work-form's efficacy was made historic by the *Manhattan Project*, which is held as the (horrifying) origin of the "modern" management of engineering projects (Lenfle & Loch, 2011).

However, since the turn of the century the productivity growth of complex integrated engineering projects has declined along with general global productivity growth (Trevelyan, 2019, p. 71). When asked about the purpose of engineering, most engineers and engineering students point to problem-solving and some sense that engineering contributes to the world, without expressing an understanding that *productivity gains* is the way in which this is achieved (Trevelyan, 2019). Most everything in engineering depends on it, even the vague but core idea of *delivering value* as another increasingly contemporary answer to what an engineer does (or should focus on doing).

Several contributing factors have been identified, which include: the escalating complexity of such projects; the diversity and interdependence of necessary expertise; and the intricacy of coordinating such multidisciplinary efforts (Mørkeberg Torry-Smith et al., 2012; Trevelyan, 2007, 2008b, 2014). Furthermore, the historical fragmentation of engineering disciplines can inhibit effective knowledge integration and exchange, further hampering productivity (Ferguson, 1992), despite decades of engineering education intervention (e.g., CDIO). In the case of mechatronics, a discipline characterized by the convergence of mechanical, electronics, and software engineering, these challenges become particularly salient (Bradley, 2004; Mørkeberg Torry-Smith et al., 2012). Hence, the need for a thorough understanding of mechatronic system complexity and the competencies required to address it effectively (Wolff, 2018).

The project work-form has long been seen as an organizing answer to the tension between emergent *complexity* of, and required *competence* for, the design of engineering systems in general (Gaddis, 1959; Pinto & Slevin, 1987). In particular, this is the case for complex multi-disciplinary engineering design projects, of which mechatronics design is an example focused on the tight integration of, and ever-rising demands for, function under severe constraints inside/across/integrating disciplines. The way that expertise and complexity in engineering projects are *perceived* as well as *experienced* thus seem to be of interest to the puzzle of engineering productivity (Johri et al., 2011; Mikkelsen, 2020b). Indeed, fifteen years ago Trevelyan (2008) stated that "*Engineering work is largely unknown except by engineers themselves and much of their know-how is knowledge that they do not know they have.*"

1.2 HISTORICAL AND CONTEMPORARY MECHATRONICS

The delivery of compact integrated physical systems under autonomous real-time motion with high accuracy, reliability, and speed requirements has for the past fifty years been the domain of mechatronics engineering. Traditionally, the core identity of mechatronics tend to be described as a holistic design paradigm of integrated development of physical systems under autonomous motion incorporating the core sub-disciplines of mechanical engineering, electronics engineering, and software engineering (Janschek, 2012). But this description tends to be offered without regard for context in time or place, apart from occasionally mentioning its industrial origin in 1970's Japan (Zheng, Hehenberger, Le Duigou, Bricogne, & Eynard, 2017). With an exception in a chapter on mechatronics in the context of the history of mechanical engineering given in Dixit, Hazarika, and Davim (2017) or the geocultural account in Hillmer (2009). As such, an account of how the academic field of mechatronics has evolved over the past four decades[1] will be given in an effort to put the concept and its perceived challenges and interest into historical context as to prepare for grounded contemporary treatment of its competencies and complexities.

1.2.1 Four decades of evolving uniqueness of mechatronic

The 80's saw the genesis of mechatronics as a unique, interdisciplinary field of engineering design research that sought to merge the principles

[1] The originating decade of the '70s will be skipped since Mechatronics represents an industrial practice concept in its origin.

of mechanical, electronic, and software engineering. The conceptual foundation of this field was characterized by efforts to develop system integration methodologies and to explore the potential of basic sensor and actuator technologies (Salminen, 1989). This was done in the tail end of the cultural phenomenon of the "miracle of Japan" which saw industrial practices of Japan dominate "mechatronics markets" (Stone, 1984).

Mechatronics in the 1990's was marked by seminal conceptual works. Beginning with the dissertation work by Buur (1990) on mechatronics in Japan, which was grounded in going there and exploring mechatronic design practice (in an admirably pragmatic fashion!) to develop foundational inductive theory of mechatronics as a field of engineering[2]. The 90's also saw the advent of a core academic interest organization: The Mechatronic Forum, a conference of which paper 3 was presented to. This forum was founded to gather the nascent academic field of mechatronics and give it a platform for discussion and collaboration. In the 1996 premier issue of one of the two central publications in mechatronics, IEEE Transactions on Mechatronics, Harashima and colleagues (1996) noted the arrival of communications technology in mechatronics during the 90's as well as being an early identifier of the MEMS-field (Micro-Electro-Mechanical System) of the 2000's. The same year, Auslander (1996) defined Mechatronics as "*The application of complex decision making to the operation of physical systems*" in the light of the increasing importance of software for machine control (e.g. automotive engine control and CNC controller). While concerned with the uniqueness of Mechatronics, Auslander tried to pin it down to consequences of computation for active control of physical systems. Already when publishing, he knew that this would probably change: "*I think that this at least lays the groundwork for a definition of mechatronics that fits current technology and has some hope of covering future developments as well.*". It did cover future developments, but not comprehensively and not for long.

The 2000s saw a significant shift in mechatronics as the field integrated rapid technological advancements, especially in data. The rise of the Internet of Things (IoT) and miniaturization efforts of MEMS and nanotechnology, together with an increased focus on energy efficiency and sustainability, marked the 00's. Bradley (2004) highlighted the transformation

[2] Small aside, this is one of my all-time favourite mechatronic works in that it combines a very pragmatic and practical attitude towards a very strong interest in theory development. I have not read it's like since.

of mechatronics into an ever more complex and data-driven field. Approaching the end of the decade, Bradley (2010) asked whether mechatronics is still distinguishable as a integration-oriented field of engineering design.

The 2010s saw a continued push for defining the uniqueness of mechatronics, against a backdrop of rapid advancements in artificial intelligence and machine learning, especially in the context of control design: Seven years ago Milecki (2015) addressed Bradley directly and offered one answer to his question: "*it seems that the direction of research related to mechatronics should be defined afresh and differences between mechatronics and other disciplines should be clearly indicated.*" However, in relating mechatronics to contemporary relevant fields of engineering design, primarily Cyber-physical Systems (CPS) and Internet of Things (IoT), has led to a tone of consolidation and a focus on "*the underlying precepts*" (Bradley et al., 2015, p. 71) of transferring functionality from the mechanical to the informational: "[…]*for the future of mechatronics, recent years have seen a shift from systems based around the interconnection of physical components in which transmitted data has been used to facilitate control,* […] *to systems in which information is at the heart of the system*." (Bradley et al., 2015, p. 59).

1.2.2 Contemporary framing of mechatronics

In the 2020's mechatronics is increasingly related to a sense of scale when contrasted to related engineering topics such as Cyber-Physical Systems (CPS) and Model-Based Systems Engineering. In a discussion of Industry 4.0, the idea of cells in manufacturing was revisited and the relation between Systems Engineering (SE) and Mechatronics contrasted and size-relations to other fields in the context of structural complexity is a contemporary distinguishing characteristic: mechatronics is distinct from CPS in that it is "smaller" (Bradley, 2010, p. 835).

The contemporary notion of mechatronics is thus contrasted based on an abstract concept of *size*, as chapters 2.4-5 in paper 5 treats in detail, and positions mechatronics in contrast to other interdisciplinary and systems-oriented practice domains (e.g., systems engineering). Interdisciplinarity is *the* core characteristic and reason for mechatronics, regardless of if one views mechatronics as a field of design, of technology, of education, or as a general a way of thinking. This is especially the case at highly detailed technical levels, in contrast to SE which likewise has the same core characteristic but focuses on high-level structure and abstract architecture.

Likewise, in terms of their system-focus, mechatronics is again more low-level and SE is more high-level (Bradley, 2010).

1.2.3 How Mechatronics perceives its own challenges

Challenges in mechatronic systems development practice has been left historically opaque and vague, with rationalistic assumptions about the shape of possible responses. The overarching needs as conceptualized by the mechatronic engineering design literature remain motivated by the most common challenges identified by Mørkeberg Torry-Smith et al. (2012). These are:

1. "*A Lack of common understanding of the overall system*",
2. "*A lack of a common language to represent a concept*",
3. "*Different mental models of the system, the task and design-related phenomena*",
4. and "*A lack of a common language to discuss freely.*".

These challenges are certainly contemporary, but they are not new. Have a look at the specifically identified "*Problems connected with a mechatronics design project*" in Salminen and Verho (1989, table 2): They not only contain the same challenges but also use the *same phrasing, 25 years earlier*. Jacob Buur (1990) echoed these concerns and it is telling that only these two seminal but aging works, together with a conference paper on A3 architecture overviews, were referenced for the most probable solutions to the four challenges which were framed as "informal descriptions" (Mørkeberg Torry-Smith et al., 2012, solution #5 in table 2). The core phrasing in all four challenges implies a fundamental assumption the role of language and understanding in mechatronics development work: that *unity* is advantageous, and *diversity* is not (Trevelyan, 2014; Winberg, 2008). The second and fourth challenge seem to connect *unity* of language to an ideal "*free discussion*" where "*concepts can be described* (uniformly)", assumed to enable a "*common understanding of the overall system*" in the first challenge. The third one is slightly more granular, recognizing general categories of system/task/process (*process* is presumed here to relate to various views of design-process' connected to different fields). While mentioning coarse categories of engineering design work, the third assumption poses diversity of "mental models" as a challenge, thus also indicating a *unity* assumption. Compare for example the *unity* in the "*Bridging Measures*" in Törngren and Sellgren (2018, pp. 498-499) or *unity* in the processes of mechatronic engineers' technology acceptance in Hillmer (2009, p. 132): "*Mechatronics is an interesting phenomenon, where engineering disciplines synergise from fragmentation to wholeness*".

This *unity* assumption is what is called a "root metaphor" assumption, which is shared across a field (Alvesson & Sandberg, 2011, p. 255). Alvesson and Sandberg gave a relevant example from management studies: they showed that the *root metaphor* assumption in seeing organizations as cultures with *unitary* set of values and beliefs (p.255) has been challenged with alternative assumptions, such as *diversity*, *ambiguity*, *differentiation*, *discontinuity*, pertinent to such cultures. R*oot metaphor* assumptions such as these alternatives are now, and have been for over two decades, increasingly common for understanding how organizations behave. These two kinds of *unity* assumptions are similar in shape, while having different "flavours" (i.e., contextual to the differences in the languages and research concerns in engineering and in management).

However, while mechatronics (like most engineering fields) recognizes the significance of effective communication, it is fundamentally predisposed towards rationalistic engineering values. Consequently, it has historically struggled to address the nuances of challenges considered to be "soft" in a theoretically grounded and in-depth manner, as Greene et al. (2017) have pointed out. Thus, the underlying issues are considered "soft concepts" and often overlooked or simplified when dealing with issues related to communication and common understanding: As when concluding with "*We should acknowledge the collaboration aspect of teamwork, and provide rooms (workshops) and methods, which will enable cross-domain discussions, and which will be graphically intriguing.*" (Mørkeberg Torry-Smith et al., 2012, p. 10).

Instead, it is this need for a "*common language*" and "*common understanding*" that gives rise to the value and fundamental call for unified system models. Which, in the ideal case, would perfectly represent functional, behavioural, and structural understandings of proposed designs. The call stands on the assumption that such idealized models would, based on the underlying objective reality of the problem space, represent a solution to the problem which can be understood in the *same way* by differing relevant stakeholders. This is so fundamentally impossible that mechatronic design research itself recognizes the ideal as being unfeasible, based on the assumptions made and for the challenges intended. Indeed, work by Tomiyama, D'Amelio, Urbanic, and Eimaraghy (2007) is often cited in mechatronics for specifically this argument, that challenges stem from an absence of a "common design methodology" (Mørkeberg Torry-Smith et al., 2012), but that the reason for this absences in turn is that "*theories building on different axioms cannot be joined to a common theory*" (Tomiyama et al., 2007). This is true when discussing theories of mathematics and theories explicitly derived from formal logic, however these core challenges do not rest on theories based on formal logic. Indeed, a presumed base in formal logic actually preclude in-depth treatment or understanding of the four challenges, for the (seemingly) simple reason that systems of formal logic cannot model human use of abstract concepts (George Lakoff & Johnson, 1999, p. 128). Instead, what the challenges describe stem from concepts and theories derived from other theories, or from inductive theory development based on empirical data on the challenges: that is, social science. Or as more relevant for these challenges, social science research into ordering modes of work (i.e., organizational science), and specifically the most common mode for mechatronic design: project organizing.

1.3 PROJECT ORGANIZING

Historically research into projects has predominantly been on the structural and procedural aspects, largely influenced by a rationalist perspective based on Systems Engineering (see chapter 3 in Paper 1)**.** This conventional approach, while providing valuable frameworks and best practices, often fails to fully capture the complexity and dynamism of project environments (Engwall, 2003; Geraldi, Maylor, & Williams, 2011; Geraldi & Söderlund, 2016). It tends to view projects as neatly bounded entities that can be managed through predetermined processes and techniques. Joana Geraldi, among others, has criticized this perspective for its oversimplification of the intricate reality of project work (Geraldi & Söderlund, 2018). Project Studies scholars highlights the need for a more nuanced understanding of projects that acknowledges the particularizing influence of context, the interplay of multiple stakeholders, and the inherent uncertainty and ambiguity of project work. This wider Project Studies perspective seeks to counterbalance the traditional, rationalistic view of project management, which they call *Type 1 project studies* (Geraldi & Söderlund, 2018). Project Studies advocates for an interdisciplinary approach that draws on insights from wider fields of organizational theory, social sciences, and humanities in what they termed *Type 2 Project studies*.

So while projects have been the standard work-form for mechatronics, Type 2 project studies bring a different lens to this process for mechatronics (Geraldi & Söderlund, 2016). In contrast to traditional project management research, it distinguishes between verb and noun: *organizing*, the active, ongoing process of coordinating work, and *organization*, which is static structures and procedures. Type 2 Project Studies focus on practice and the lived experience of project participants, rather than solely on formal structures and processes. This attention to the human, dynamic aspect of mechatronic project work provides an opportunity for a different gaze towards the needs of mechatronic design (e.g. Trevelyan, 2007, 2008a; Trevelyan, 2019). Indeed, in quoting Winter, Smith, Morris, and Cicmil (2006), Geraldi and Söderlund (2016) maintained that common techniques often fail to answer "how"-questions to *"navigate the complexity of projects in the ever-changing flux of events*", pertaining to all project participants. Therefore, a core concern for project studies (research) and project work (practice) is that of understanding the nature of this inherent complexity. Especially in Winter et al.'s "*ever-changing flux of events*" that is the actuality of lived project experience. Additionally, that the Type 2-view stresses the importance of the contingency of such lived project experience on specific technical knowledge and understandings (Geraldi & Söderlund, 2016), meaning that technical knowledge and issues experienced inside Mechatronics need the perspectives of Mechatronics for relevant understandings, even if those are supported by "outside" theories or views (such as from organizational science).

1.4 THESIS PURPOSE AND RESEARCH QUESTIONS

Having established the project organizing-perspective as a way to challenge the assumption of *unity*, an approach by Alvesson and Sandberg (2011, p. 232) is used to shape thesis purpose and research questions. It deploys problematization rather than gap-spotting to "*come up with novel research questions through a dialectical interrogation of one's own familiar position, other stances, and the domain of literature targeted for assumption challenging."* (Alvesson & Sandberg, 2011, p. 252). My own familiar position is that of being torn between epistemological norms and research conventions of two very different fields (Mechatronic Design and Project Studies), and of being suspicious of realist representations due to a preference[3] for constructivist notions of knowledge and the social world.

Building research questions through problematization consists of six steps (Alvesson & Sandberg, 2011, figure 1): First, identify the relevant literature domain; Second, articulate its assumptions; Third, evaluate and

[3] Due to this familiar position, it was quite challenging to choose embodied and social realism as a base for the thesis, even when I saw good reasons to do so. The realist stance was taken and is discussed in chapter 5.2.1.

challenge those assumptions; Fourth, develop alternative assumptions; Fifth, identify the relevant audience holding the challenged assumptions; Sixth, assess whether the alternative assumptions can generate a theory which is interesting to that audience. Step one through three was covered above. The four mechatronic challenges can be rephrased as to more clearly show the underlying stance it inherits: "*Speaking differently is a barrier to free discussions in which to representing concepts so that the team can construct and maintain a shared system overview, and different mental models of the system, the task and design-related phenomena is the reason why this is so difficult.*"

The alternative assumptions come from introduced Type 2-perspective and they are developed further in papers 1, 2, and 5. Synthesized to a single statement for the purpose of the thesis, I offer the following alternative assumption**:**

> Alternative assumption 1: *Diversity in understanding and language is a fundamental feature of mechatronic design and should be expected on principle and recognized in its particulars for each situation.*

This is an alternative assumption to *Unity*. Note that I am *not* saying that we mechatronic engineers explicitly hold the opposite to be true: We of course know about this as such. However, a consequence of this assumption must be that, since Mechatronic project work is characterized by this diversity, and it cannot be avoided, both the competence required for it, and the complexity inherent to it, must then also be characterized by a *Diversity*-assumption instead of common *unity*-oriented logics. This leads to a second assumption.

> Alternative assumption 2: *The nature of complexity for both system and project concerns how diverse its perception is on both the individual and group-level, and the competence to know that.*

The fifth and sixth step assures relevance of the proposed alternative assumptions. To be useful to the audience holding the challenged assumptions, which is the mechatronic design research community and early-career mechatronic engineers, these two must reasonably be expected to generate theory or results of interest to this audience, as well as to the original need embedded in the four original challenges. The perspectives afforded by the Type 2 Project Studies on project organizing which motivate the two alternative assumptions should reasonable be expected to give helpful detail to the four challenges in a way that mechatronics historically and contemporarily have been unable to do for the reasons given above.

Thus, having problematized the understanding of identified challenges and offered alternatives, this thesis aims to: *explore the generation of perceptions of engineering expertise and complexity in the lived experience of mechatronic project work*. based on the alternative assumptions, it aims to provide increased conceptual clarity through theoretical grounding to how mechatronics as a field of engineering design research understands its own challenges. Therefore, the thesis poses the following research questions on the micro-meso level between the individual and the team:

> RQ1.1: *How do mechatronic project members perceive expertise in the lived experience of their projects?*

> RQ1.2: *How do mechatronic project members perceive complexity in the lived experience of their projects?*

> RQ2: *What constitutes the experiential relation between expertise and complexity in mechatronic project work?*

1.5 Thesis structure

Chapter 1 introduces the research context of mechatronic project work and details the problem. Through the two relevant fields of *Mechatronic design research* and *project management research*, the thesis nested context of *mechatronic project work* is established, assumptions are explicated, challenged and alternatives are offered. Chapter 2 constructs a theoretical frame, based on papers 3, 4, and 5, for how this thesis understand *Complexity*, *Expertise* and *Metaphor*. Chapter 3 describes the overall research design and each individual methodology of the five appended papers. Chapter four serves as a summary and reading guide for those papers. The research questions are addressed in chapter five by using the presented research design and based on the theoretical framing of the work in the compiled works (papers 1-5), a framework of the results is synthesized in chapter 5. Figure 1 visualises the thesis structure.

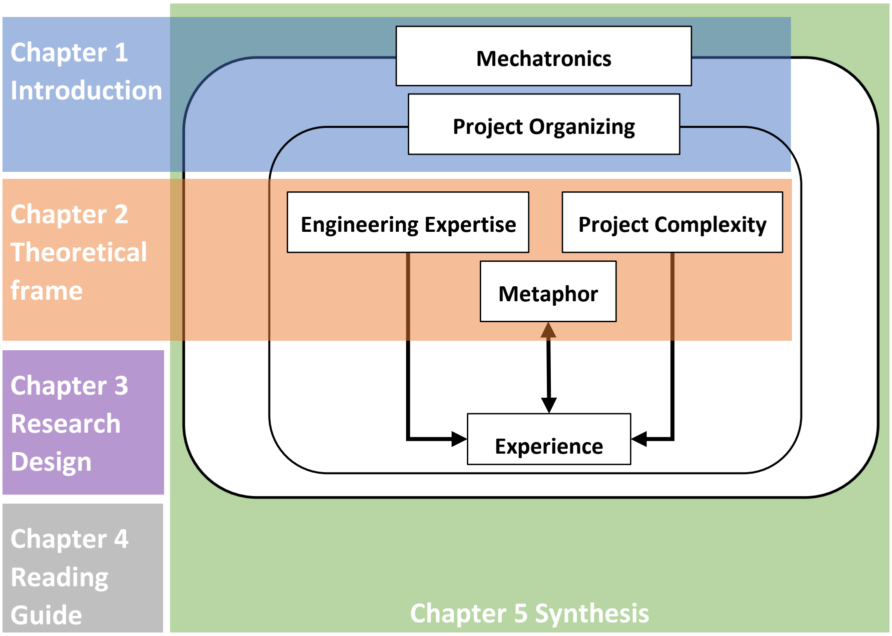


Figure 1: Thesis structure overview

2 THEORETICAL FRAME

The thesis' theoretical frame is two nested contexts, projects inside of mechatronics forming *mechatronic project work*, containing two tensioned concepts, *complexity* (2.1) and *expertise* (2.2), which are understood on a micro-meso level in their nested contexts using a cognitive linguistic theory of metaphor (2.3). Together they focus the area and direction inquiry and the logic of the overall approach for this thesis. Individually the concepts also ground the specific approaches in each of the five included publication to varying degrees. As *Expertise* and *Complexity* has been theoretically treated extensively in papers 4 and 5, they will be summarized, and the reader is referred to their respective paper subsections. Only *Metaphor* and the theory used to understand and use it will be extended further here.

2.1 COMPLEXITY

The evolution of viewpoints on complexity historically started quite similar for research in both mechatronics and in projects (Bradley, 2010): Both research fields have structuralist and rationalist twentieth-century roots in systems engineering, but over time has (in part) deviated from each other. The details of this evolution, from Baccarini (1996) through Williams (1999); (Williams, 2005), Geraldi et al. (2011), to Bakhshi, Ireland, and Gorod (2016), was treated extensively in chapter 2.1-2.4 in Paper 5, which the reader is recommended to read now.

The theoretical position established there on perceived complexity, based on a Type 2 Project Studies perspective, is reasserted here with one extension. Paper 5 and the thesis as a whole differ in positioning in the complexity research typology of Mikkelsen (2020a, table 3): paper 5 aligned closer to an ideal type 5 of complexity research in its interest to understand its case as a critical case, while the thesis as a complete work has a stronger pragmatic micro-meso-oriented interest in addressing mechatronic challenges. This interest puts the thesis between an ideal type 5 and type 4, because type 4 describes the stronger pragmatic interest in what to *do* with perceived complexity rather than simply describing what *it is*. Therefore, the thesis takes a broader and more pragmatic stance towards complexity, seeing it as perceived but lifting the analytical gaze above paper 5's singular concern to understand the case study. Pragmatically and grossly put: *Complex* ➔ *difficult and important*.

2.2 ENGINEERING EXPERTISE

The idea of expertise and competence in any professional area might at first seem tacitly hidden, wholly contextual, and opaque. However, the general features of engineering expertise are well-established across a large number of studies where expertise "*largely consists of a series of elaborate socio-technical performances that are remarkably similar across all disciplines*" (Trevelyan, 2019, pp. 282-283), which seem to be specifically the case for mechatronics (Wolff, 2018). Legitimation Code Theory (LCT) is a sociological realist framework for researching knowledge-building which serves the thesis to "…*enable the generative theorization of practices that are unrealized empirically or have become obscured.*" Maton (2016, p. 17). The theoretical position established in Paper 4 in chapter 2.1-2.3 is also reasserted here. Specifically, in how it characterizes expertise in 2.2. based in an *integrative*-view of skill and how LCT is made pertinent for understanding this view of expertise and how it relates to perceiving complexity in 2.3.

2.3 THE INTEGRATED THEORY OF PRIMARY METAPHOR

Metaphor tends to be viewed as a novel feature of literary or poetic language. However, as employed here metaphor is used as a cognitive lens through which to explain the direct everyday experience of abstract concepts, as opposed to its common usage. This perspective is based on an embodied realist position (Johnson & Lakoff, 2002) which it holds that a person's ongoing bodily experience and physical interaction with their surroundings structures both their *thoughts* and their *actions*.

This kind of metaphor is called a conceptual metaphor, and from the embodied realist position it structures thoughts and actions through connecting concrete physical experiences to abstract conceptual domains (Lakoff and Johnson 1999; Lakoff 1990). George Lakoff and Johnson (1999, pp. 46-47)'s integrated theory of primary metaphor (ITPM) constitute one such embodied realist position. ITPM explains how abstract concepts are subjectively experienced through objectively existing structures in the body and brain. The four theories which constitute ITPM are detailed in chapter 2.4.2 in Paper 5. Gibbs, Lima, and Francozo (2004) argued that one of the most important progressions in metaphor theory since the early 80's has been cognitive science research data showing that metaphor is not simply a part of flowery and descriptive language: Rather, it constitutes a fundamental part of people's day-to-day experience in thought, reason, and imagination. Indeed, Gibbs and his colleagues argue that cognitive linguistic studies reveal that a significant portion of human cognition is not represented as propositional or sentential information. Instead, it is based on and organized by various patterns of our perceptual interactions, bodily actions, and our manipulation of objects. Meaning that such patterns are integral to *thinking*: Cognitive and developmental psychology research provides evidence that sensorimotor representations of imagery are crucial to numerous forms of higher-level perception and thinking (Gallese & Lakoff, 2005; Johnson & Lakoff, 2002; George Lakoff & Johnson, 1999). Indeed, a significant consequence of this for conceptual metaphors is that many of their source domains reflect these significant patterns of bodily experience.

But what is a conceptual metaphor, source domain, and target domain in this embodied realist view? *Love is a Journey* is a conceptual metaphor that takes a more concrete physical concept (*Journey*) as a source domain and connects it to a more abstract concept (*Love*) as a target domain. By relating the concept of love to the concept of journey, we can express and understand complex aspects of love in more concrete ways which are, crucially, *activated* in our bodily understanding of movement and travel and time.

2.3.1 Bidirectional activation

Metaphor activation is this bidirectional relation between physical perceptions/sensations and primary metaphor: an example (from recent lab-experiments, see Hampe (2017)) show how raising room temperature can affect a person's judgment of another person or situation as friendly, with the reverse also being true, in thinking about a friendly or unfriendly social situation can alter an individual's experience of room temperature. This is an example of the bidirectional activation of the metaphor FRIENDLINESS IS WARMTH (Shen and Porat in Hampe (2017)). Importantly for the thesis framework (chapter 5), activation is bidirectional, going not only from the source domain (sensing heat) to the target domain (friendliness), but as we saw in the example above that being treated nicely makes one experience physical warmth and the framing of that that sensation is not that the body is heating itself up but that the situation is *causing* the physical process of bodily heat. Crucially, using this lens, this is causally true from an embodied realist position:

> *In situations where the source and target domains are both active simultaneously, the two areas of the brain for the source and target domains will both be active. Via the Hebbian principle that* Neurons that fire

together wire together*, neural mapping circuits linking the two domains will be learned. Those circuits constitute the metaphor*. – Lakoff (2008)

2.3.2 Why use metaphor to understand mechatronic project work?

ITPM serves to theoretically motivate the alternative assumptions and supports a position from which to address the second research question, affording an explanation of the experiential constituents of expertise and complexity. As *expertise* and *complexity* are both highly abstract and complex concepts they are constituted by and experienced through several integrated primary metaphors as complex metaphors (see chapter 2.4.2 in paper 5). Gibbs (2013) argues that individual metaphoric cognition is implicitly social because it is shaped by social experiences and interactions. For example, the common metaphor ARGUMENT IS WAR is learned through social interactions and even when used in the privacy of one's own thoughts, such metaphor still shapes social experiences in turn. In the context of mechatronics such common metaphors include ENGINEERING IS PROBLEM-SOLVING. Therefore, metaphoric cognition cannot be separated from social activities and discourse.

Furthermore, mainstream organizational journals have established the value of understanding organization and work through metaphor in general (Cornelissen, 2005)**, and particularly when taking an embodied realist position** (Heracleous & Jacobs, 2008). Andriessen and Gubbins (2009) argue that metaphors play an important role in theorized representations of organizations, giving *social capital* as an example which is used metaphorically (RELATIONS ARE A RESOURCE), offering a wide range of entailments useful in theorizing about relationships in organizations.

Understanding and theorizing temporary organizations such as projects through metaphor affords empirical access to low-level interactions and phenomena (Shelley, 2012; W. Shelley & Maqsood, 2014). It also affords a way to understand central overarching questions for projects, such as work by Burström and Wilson (2018): They used the concept of metaphor to investigate what they called the "*texture of tension*" for development projects. While of value to project studies, such studies rely on the conventional conception of metaphor as a novel linguistic device used to express something new about something known. Organizational studies and project studies such as those above tend not to take an embodied realist position and does not use a cognitive view of concepts as embodied. Indeed, Burström and Wilson (2018) simultaneously recognize and miss this prelanguage value of the embodied view in their first sentence and first paragraph, as follows: "*Practically, everyone who has worked on a project knows the feeling when walking into the project war room and the air is filled with tension. You just know that it is going to be a hot meeting where people for various reasons try to restrain themselves from bursting out in harsh words*". This is a good and strong first sentence for their paper. It captures the article's problem situation and positions it well. However, it then misses the potential deeper value when in the next sentence saying *"it is difficult to explain this feeling*", which of course is true since it pertains to embodied pre-linguistic representations of abstract concepts (i.e., our position: embodied conceptual metaphor).

Consequently, since they maintain no such position, they cannot explain this tension which "everyone who has worked on a project knows" further than with a naturalizing reference to common sense: "*In the popular parlance, it is manifested by a 'knot in the stomach, weakness in the knees, or hair bristling on the back of the neck.'*". Such knots, weaknesses, or bristling of parts of the body are what constitutes the *realist* part of embodied realism, and it is in such subjective experiences that the objective existence of abstract concepts is found. It is the reason for why this first paragraph so powerfully captures the entire article: it intuitively rests on an embodied understanding of tension to motivate it, implicitly. For this thesis I do so explicitly, using ITPM in mechatronic project work.

ITPM is specifically relevant for mechatronics because it can uphold the offered alternative assumptions. Wolff (2018) stands as a mechatronic example of using an explicit conceptual metaphor that maps to the *unity* assumption without offering an alternative assumption: "*As such, the research design employs a metaphor drawn from the empirical site* [mechatronics] – *that of an integrated modular system.*" Using this highly structured metaphor is apt for its purpose in Wolf's article, but in constructing it metaphorically on mechatronics it reproduces its *root metaphor* assumption.

Now you should see how abstract concepts, both simple ones such as *numbers* or *time* as well as complex ones such as *corporation*, *team*, *complexity*, *tension* or *product development*, grounds their objective existence in the form of embodied conceptual metaphor. ITPM will be used in chapter 5 to synthesize a framework of the results, summarized in chapter 4, to address the research questions. The research design which the thesis employs to enable such synthesis will now be explained.

3 RESEARCH DESIGN

The purpose of a compilation thesis research design is to present the logic upon which the research questions were answered *through the included works*, together with the process tying these together. A good way of communicating this process is accounting for the reasoning behind the methodological choices made. Therefore, this chapter will start thusly describing the research process, which will start with the basic logic and how it on an early staged turned and changed, such change being common for PhD thesis research. Methods for data collection and analysis will be summarized. Finally, criteria for assessing the trustworthiness of the thesis are discussed.

3.1 RESEARCH PROCESS: A NARRATIVE ACCOUNT OF METHODOLOGICAL CHOICES

The fundamental concerns guiding the methodology was that from an early stage the thesis took an *abductive* and *exploratory* stance towards its purpose of investigating mechatronic project work. This was a departure from the initial direction which was deductive and prescriptive in its desire to detail how mechatronic design work *could* be organized, with an aim to develop a process framework model for such work as research contribution. The early turning towards a more open, dynamic, and critical stance originated from a pragmatic interest in real-world causes of the mechatronic challenges discussed in the introduction: "*The pragmatic approach is to rely on a version of abductive reasoning that moves back and forth between induction and deduction*" (Morgan, 2007, p. 71). Indeed, abduction allows for the explorative and nonlinear research processes of this thesis (Thomas, 2010). The initial conceptual work in Paper 1 was conducted to understand the two included research fields and to establish the thesis' basic stance, and it motivated this abductive and explorative turn.

After conceptually mapping out the two research fields of mechatronics design research and project management, it became clear that the interests and viewpoints of Type 2 Project Studies best served the concerns of the mechatronic design literature in three ways. First, Type 2's empirical setting concerns very specific types of project and project contexts as opposed to traditional project studies (Type 1) which generally maintain a universalizing stance towards project types/contexts. Second, the theoretical grounding of Type 2 project studies is not limited to project management, opening the thesis to other viewpoints. Third, there is a focus on descriptive contributions to practice as lived experience in what Type 2 research calls the "*actuality of projects*" (Geraldi & Söderlund, 2016, p. 773). Based on the developed alternative assumptions of mechatronic challenges and the fundamental pragmatic stance of the mechatronic research field, this focus serves well.

To further strengthen this connection between mechatronic and Type 2 Project Studies a discursive analytical stance was chosen (Alvesson & Karreman, 2000). The work in paper 2 proposed a discursive model which questioned the predominant view of mechatronics as a stable concept in terms of its core epistemic relations: the idea of the integration of mechanical engineering, electronics engineering, and software into mechatronics. Furthermore, to question the idea that those core disciplines remain stable while other contexts change and subsequently be perceived as less relevant to the identity and definition of mechatronics compared to that "core". During this part of the thesis I saw how sensitive to context definitions might be, and that the *unity* assumption of mechatronics in addressing its challenges seemed even less tenable than the misgivings I saw in many concluding paragraphs from initial readings of the mechatronic design literature (e.g. Bradley, 2010; Bradley et al., 2015; Mørkeberg Torry-Smith et al., 2012). A step back into a more pragmatic and granular position was deemed necessary.

Stepping back, it was at this point that the aim to specifically explore what generates perceptions of *expertise* and *complexity* in mechatronic project work arose. These two concepts abductively drove the research design's selection of methods, data collection as well as data analysis procedures, while the empirical setting of the research design was set by the thesis' primary mechatronic context. Therefore, the thesis' abductive reasoning process (Figure 2) started from this position (in papers 1 and 2).

Stage I: From the starting position an inductive exploration mapped out general themes of complexity in *lived experiences of* complexity in the *actuality of a mechatronic project*. An exploratory case study design (Yin, 2014) was chosen with data collection through exploratory interviews, appropriate for such designs (Brinkman & Kvale, 2014, InterViews), triangulated with observations and documents. The data analysis was carried out through thematic analysis.

Stage II: The thematic results in the third publications relating to mechatronic design challenges motivated a first abductive pivot to a

deductive interest in perceptions of engineering expertise. Using a structured survey design, hypothesis-testing was carried out through ANCOVA and Correlation tests on the idea (see figure 4 in Paper 4) that perceptions of the constitutive nature of engineering expertise differ over how the engineer understands their own role in the initial career, but that such differences should lessen as engineers progress into their careers.

Stage III: A second abductive pivot back to an inductive investigation of complexity dimensions drove the work reported by the fifth paper. This was motivated by the confirmation of the fourth paper's two hypotheses and it finding that three themes of bias were present: The difficulty represented in *academic performance bias*, *technical expertise bias*, and *rationality bias* for early engineers motivated a more focused look at how complexity is *experienced* in mechatronic development project as a *lived practice*. That made it appropriate to investigate the case study with an aim to explicate interactions of perceived complexity dimensions.

This concludes the account for the methodological choices taken.

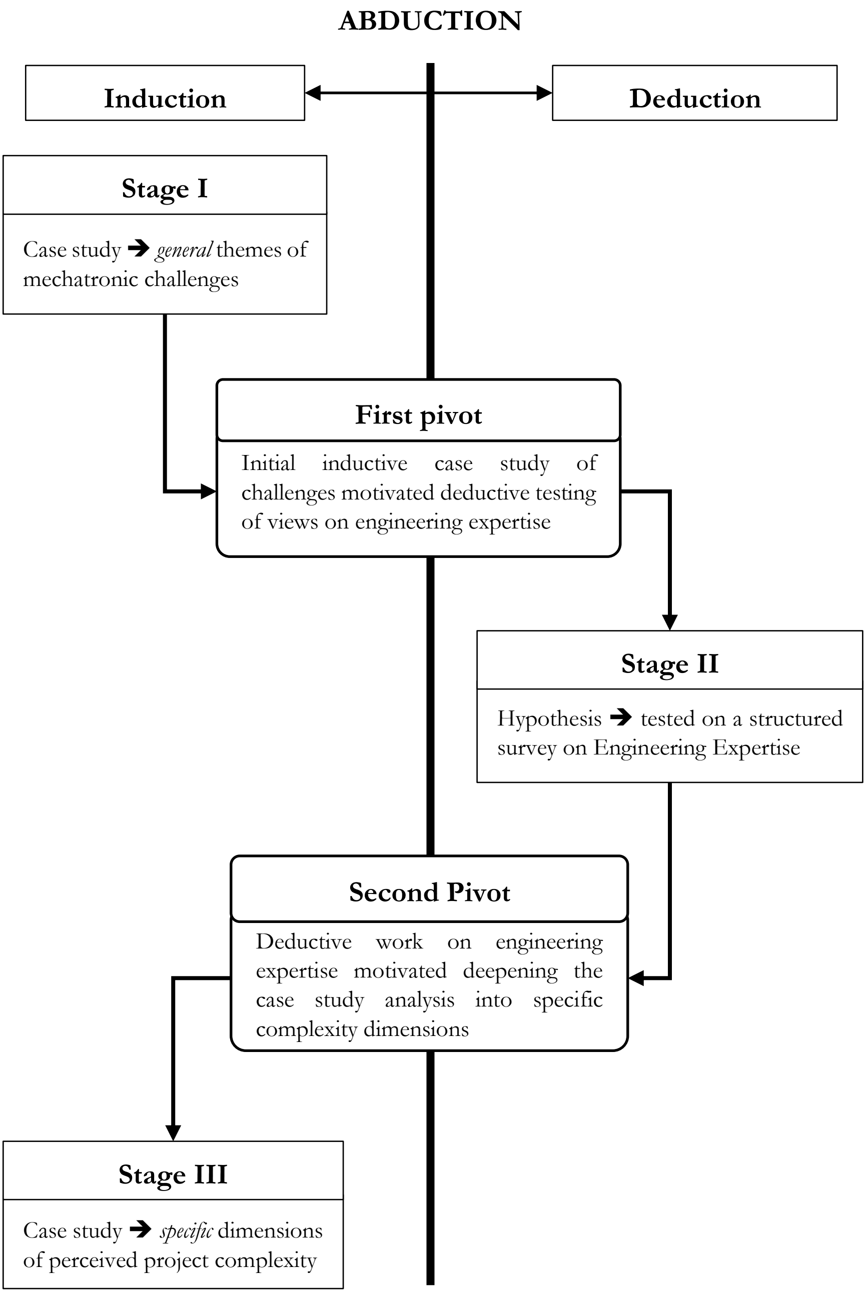


Figure 2: the thesis' abductive reasoning structure

3.2 DELIMITATIONS AND ROADS NOT TRAVELLED

Creating a nuanced and deeper understanding of definition(s) of mechatronics was the driving force behind the work in paper 2. The choice not to design a study using an expert elicitation method (e.g. a Delphi method (Okoli & Pawlowski, 2004)) as to iteratively elicit an empirical consensus on defining mechatronics was quite simple. It rapidly became obvious in the early conceptual stages of Paper 2 that views diverged so strongly over contexts of practice (large or small industry firms, focused or broad academic institutions) and over geographical location as well as over simply what task that "mechatronics" were seen to be supposed to solve, that *useful* consensus were not deemed reasonable to be expected as a result.

Instead, a more conceptual interest was taken towards this dispersed view-taking, which was additionally found to be supported by comments in the literature, such as when Bradley asked whether "[…]*to provide any form of expression of mechatronics, whether textually or graphically, may of itself be a source of confusion and that it may therefore be better for mechatronics practitioners to operate within their own particular context than to attempt to conform to a specific and overarching definition?*" (2010, p.828). However, I did not fully take the suggested route. Refusing to *operate within* one's own context but accepting *not to conform to an overarching definition*, a conceptual mapping of a potential discursive structure for mechatronics definitions was made in paper 2.

The choice not to attempt direct measurement or observation of metaphoric activation came from the fact that it is methodologically questionable to what extent this is at all possible. Especially in the context of practice-oriented approaches to researching the lived experience of project work. This stands in contrast to a more experimental and controlled setup where situations and measurement constructs could be designed and anticipated and thus controlled for. Take the Direct metaphor elicitation technique as an example: Direct elicitation as a measure of metaphor use has several limitations that need to be considered (Wan, 2011). It relies on participants' ability to directly express activated metaphors through language, which can lead to inaccurate capture of participants' conceptualizations. The use of direct elicitation may not capture the full complexity of participants' metaphor use and consequently missing the nuances of their thinking.

Therefore, it can be fruitful to consider alternative methods for identifying metaphor, such as analysing language use in naturalistic settings (Wan, 2011).

Instead, the abductive approach of the thesis serves to support such an alternative inductive inferential strategy on the explorative interest in metaphor.

3.3 DATA COLLECTION AND ANALYSIS

Having discussed the most important choices made, I now turn to the empirical material and its individual collection and analysis procedures. To answer the research questions on *how complexity and expertise is perceived*, I used a mixed method approach which included semi-structured interviews, surveys, observational procedures, extensive readings of internal documentation and IT-system analysis (for validating and triangulating case study data). The research purpose of Paper 4, to investigate differences in skill-perception by measuring engineering expertise in a skill-integrated manner, maps onto the thesis research question 1.1 to explore *how expertise is perceived*. Similarly, the purpose of the fifth paper mirrors thesis research question 1.2 to explore *how complexity is perceived*. The individual data collection and analysis procedures have been extensively described in Papers 3, 4, and 5 in their respective sub-chapters: the reader is referred to chapter 3.3-3.4 in Paper 4 and to 3.3 in Paper 5. However, for summarizing purposes a table of the empirical material collected, and its collection method is presented below.

Collection method	Data collected
	The Case Study (Papers 3 and 5)
Semi-structured Interviews	• 11 interviews with project team (PM twice)
Observations	• Spent several days per week at the site for three months, • Numerous informal interactions,
Document analysis	• system part database, • Business canvases, • meeting documents, • project documentation,

	• steering committee meeting minutes, • FMEA documents, • Requirement documentation, • Product development process descriptions, • Product development reporting documents, • team meeting minutes, • standing pulse meeting stack documents, • Windchill backlog, • JIRA system,
The Structured Survey (Paper 4)	
Electronic survey – Part I	8 items measured career path, perceived work role, and competency profile
Electronic survey – Part II	12 items measured to what degree that the respondent's understanding of engineering expertise aligns with the skill-integrated view of expertise used in paper 4 and the thesis.

3.4 CRITERIA FOR ASSESSING THESIS TRUSTWORTHINESS

The thesis must establish a logic to assess its quality and trustworthiness. It does so by adhering to interpretive quality criteria given by Schwandt, Lincoln, and Guba (2007); Yin (2014) and supported by the reflexive stance in Alvesson and Sköldberg (2009, pp. 304-305). The below table accounts for the necessary criteria, what they mean, and how the thesis address each.

***Criteria* – explanation**	**Assuring trustworthiness by:**
Reliability – how the findings appear to be	1. Holding a workshop where the interviewees verified the interpretations of the data obtained in the case study;
	2. Using a case study protocol and a contract was signed with the firm to establish the nature and scope of the study and principles for publishing;

representations of the data	3. Triangulation of empirical sources between interviews, documents and observations was made.
	4. Used an established framework for designing and conducting statistical tests (see paper 4).
External validity – how the findings apply to other settings	1. Having a strong theoretical foundation to enable theoretical generalization.
	2. Establishing a replication logic for the case study in the case narrative, enabling its replication in other settings.
	3. Maintaining transparency in case study analysis (Yin, 2014, p. 37).
Dependability – how the explanations are stable and consistent	1. Matching all respondents in the survey and subjects in the case study with the intended data demographics. Mechatronics alumni for the survey study and a core mechatronics development team for the case study;
	2. Having used secondary data, including internal reports.
Confirmability – how research bias is handled	1. Using triangulation and pattern-matching in the case study.
	2. Asking participants in the case study to verify interpretations during interviews and after observations.
Integrity – how misinformation or evasions by participants has been handled	1. Having no contradictory evidence identified via triangulation of empirical material sources.
	2. Signing an NDA for the case study to ensure confidentiality of obtained empirical material, Survey tested and analysed on group-levels and as such no results traceable to any participants.

4 PUBLICATION SUMMARY

4.1 READING GUIDE

The reader is advised to stop here and read the five papers appended to this thesis in sequential order (1-5). Doing so will enable engagement with the thesis' research findings on the lived experience in mechatronic project work through its complexity and expertise. It will also be assumed for reading the next chapter on the synthesis of the individual results into the thesis framework.

The most specific contribution of each paper to the thesis is summarized in the below table. The initial two papers serve as a conceptual basis for the empirical work in the last three papers. The rest of this chapter serves as extended publication summaries.

Paper	Type	The paper contributes to the thesis by
1	Theoretical	*Relating* the research fields of project management and mechatronics to each other through three conceptual models
		Investigating mechatronics and PM's histories, values, methods, and application-areas
2	Theoretical	*Framing* mechatronics through a *Grand* and *loosely-coupled* discursive stance as the central thesis context
3	Empirical	*Eliciting* four emergent general themes of complexity in mechatronic project work
4	Empirical and theoretical	*Establishing* a view on the nature of expertise for mechatronic team members
		Finding three types of bias hindering recognition of legitimate basis for practice (i.e., expertise), using LCT
5	Empirical and theoretical	*Establishing* a metaphoric basis for perceived complexity in mechatronic project work

4.2 PAPER 1

Contribution to thesis:

Paper 1 contributed conceptual groundwork to the thesis by relating Type 2 project studies and mechatronic design. It motivated an abductive and explorative stance for the thesis. The three models, especially the third inclusive conceptual model, enables the integration of both mechatronics and projects as context-frames for the thesis, thus recognizing mechatronic design projects an essentially social process with an intricate technical core.

Purpose: To lay down conceptual groundwork to support working across research fields that have different languages and norms, aiming to relate the two academic fields of Mechatronics and PM together.

Methodology: Taking inspiration for the conceptual treatment of mechatronics and PM from the approach of Greene, Gonzalez, Papalambros, and McGowan (2017) who compared the history, values, applications, and methods of design thinking and systems thinking in engineering and proposed four concept models. Paper 1 proposed three concept models.

Findings: Project Management and Mechatronic Design both aim to build knowledge around some aspect of design (i.e. system design/project design), and depending how one chooses to see them, they are either close (e.g. Type 1 project studies and mechatronic design research) or far away from each other (e.g. *unity* vs. *diversity* assumptions in Mechatronics vs Type 2 PM).The concept models display three ways for relating them: The first best explaining how they are very different; The second show how they have some common ground (especially in Type 1 PM and mechatronics); The third (inclusive) model is more useful for understanding mechatronic design and projects due to its recognizing of the context dependence of project practice (Type 2-view).

Research implications: The paper laid conceptual groundwork for future research relating PM to mechatronics, both in their research and practice. Any researcher wanting to explore complex product development projects needs to recognize that they are studying an essential social process with an intricate technical core (Geraldi & Söderlund, 2016).

4.3 Paper 2

Contribution to thesis:

It gives the thesis a *Grand* and *loosely-coupled* discursive view of mechatronics as central context for the thesis as a whole, and for the included papers.

Purpose: To interrogate the discursive structure of mechatronics' definitions.

Methodology: Discourse analysis as described by Alvesson & Karreman (2000, fig. 2). Here discourse has two dimensions: between long-range and close-range interests (*Macro/Meso/Micro context*) and between viewing discourse as inseparable or autonomous from meaning (*Discourse determination/autonomy*). The theoretical details of these two dimensions were not explained at length in paper two, but referenced, due to space constraints and a judgement that for the specific publication, audience and the aim of the paper it was not critical. However, because of this these details will be further discussed in chapter 5.2.1.

Findings: The discursive frame for understanding how mechatronic definitions evolve affords a more open perspective. The paper delivers a "reminder model" likened to the V-model (Mooz & Forsberg, 2006, p. 1368), serving when investigating mechatronic actors. Because, also like the V-model, it does not include, nor does it aim to describe, a complete structural or operational logic for its modelled phenomena, but rather to emphasize some important aspect of it. So, for the V-model it is the coupling of system decomposition with test-planning, and for this paper it is the *Grand loosely-coupled* modelling of the discourse of mechatronics definitions. The model supports a multiplicity-view of definitions coupled with a cyclical dynamic relationship between definitions, contexts, and actors.

Research implications: The paper provides a logic for nuancing, if not immediately shutting down, armchair argumentation on any core nature or "ground truth" of mechatronics into a more realistic and pragmatic view on its various practices (industrial, academic, educational), of which the industrial engineering practice of designing and delivering mechatronic systems through the project work-form serves as the context of interest for this thesis.

4.4 Paper 3

Contribution to thesis:

The third paper contributes with emergent general themes of complexity in mechatronic project work to the thesis. These constitute Stage I of the research process, motivating the first pivot.

Purpose: To take a position in the discussion on the next steps for mechatronics. The paper was exploratory, and the purpose of its empirical investigation was to generate questions and research directions related to the nature of complexity in mechatronic project work.

Methodology: An exploratory case study was conducted on a mechatronic product development project at an industrial tool developer. The case study of the project deployed semi-structured interviews, observations of meetings and workplace interactions of the project team. The interviews were exploratory and thematically oriented towards tools, processes, workday, and role. These themes where initial structuring devices for the interviews, and they changed with the interviews as some of them, *processes* and *workday*, were shown to be more conducive to rich discussion of the how the interviewee experiences the project than *tools* or *role*. This structuring approach is in line with the emergent properties of exploratory interview techniques, and how such techniques might be deployed in an exploratory case study design.

Findings: The emergent themes of the different data collection efforts, from the initial themes above, were *Technical Complexity*, *Requirement Management*, *Internal Communication & Planning*, and *Cooperation*. These four themes emerged out of the interviews of the project members and the observations of their interactions both within and outside the core project organization. While these four themes are strongly interlinked, they were connected to four of Tory-Smith et al. (2012)'s challenges: *Difficulty in assessing the consequences of choosing between two alternatives*; *Lack of broadly accepted methodology*; *Synchronizing development activities to attain concurrent engineering*; *Different mental models of the system, task and design-related phenomena.*

Research implications: The paper, in the context of mechatronics engineering education, questions the relationship between mechatronic sub-disciplines and the increasing importance of what is perceived as the "software-part". This might be described as a third incarnation for the role of computer software in the history of mechatronics. First, as a support tool for design of mechanical and electrical engineering, then secondly taking a more real-time control and overall decision-making role for mechatronic systems. Thirdly, it might increasingly assume a development support role, but this time in a holistic sense, such as what can be seen in functional modelling and MBSE, and not only for mechanics/electronics.

4.5 PAPER 4

Contribution to thesis:

Establishing a view on the nature of expertise for mechatronic team members and using LCT to extend this understanding to three types of bias hindering expertise (code-clash). High degrees of complexity (theorized as high semantic density) associate with both the ability to *recognize,* and *collaborate* within, legitimate basis for practice, seemingly mediated by the theme of rationality bias.

Purpose: The study starts from an *integrative*-view while questioning a *universalized*-view of engineering skill for the early career (see chapter 2.1 in Paper 4), leading to an operating definition of professional skills which integrates technical knowledge into *engineering expertise*. The purpose is to see if differing views of expertise could be found between initial career trajectories, indicating misalignment on professional skills. Paper 4 was supported by two dimensions of LCT that theorize knowledge-knowers relations and context-complexity aspects of meaning.

Methodology: Paper 4 investigated a professional skills readiness difference between initial career trajectories (hypothesis 1) through an analysis of engineering expertise perception, and whether this difference decreases over time as engineers mature (hypothesis 2). An integrative-view of professional skill must be taken into methodological account to measure skills-perceptions in early (mechatronic) engineering practice. Therefore, Paper 4 puts the division between the "technical" and "non-technical" on the analytical level rather than on the level of data collection by using engineering expertise as a skill-integrated measurement construct.

Findings: Both hypotheses were supported by three statistical tests which established the specific nature and size of this difference. Three themes were identified: Academic bias, Technical competence bias, and Rationality bias. Thematic analysis through the framework of these three themes indicates how context and complexity (Semantic dimension) and Knowledge and Knower (Specialisation dimension) were understood in practice. The three themes expressed challenges over these two dimensions in understanding Technical knowledge, Collaboration, and the Legitimate basis for practice.

Research implications: Engineering educators should be mindful to motivate the need for professional skills to students, as they can end up in different practice contexts. However, practice-oriented parts of curricula can never fully represent actual practice but can be valuable in making own attitudes visible to students and changing them. Future research could dive into developing a deeper understanding of the semantic codes and specialization codes of the three themes.

4.6 PAPER 5

Contribution to thesis:

A more theoretically grounded (ITPM) and granular view of complexity, and a metaphoric basis for perceived complexity.

Purpose: Researching perceived project complexity requires a sensitivity to and focus on context. "Smallness" is an under-researched project context of size, relevant for the practice context of Mechatronic systems development projects. This engineering practice context necessitates a compacting synergistic integration of development work in small tightly integrated multi-disciplinary development teams. It also raises the question of how small projects might express complexity.

Methodology: The study explored a single critical case study to investigate the lived experience of project members in a small mechatronic project by triangulating interviews, observations, and documents. An integrated theory of metaphor was used to explain their various experiences and expressions of project complexity.

Findings: Four drivers of project complexity were found, and a potential metaphoric causal structure of how these relate to "smallness" were offered as an answer to Paper 5's research question.

Research implications: The exploration of perceived project complexity using metaphor-theory is both original and useful in its ability to make sense of the lived experience of abstract concepts and connect these to direct subjective experience. Especially for understanding the relation of "smallness" to project complexity in a practice context such as mechatronic project work which is expected to be both complex and "small".

5 SYNTHESIS OF RESULTS

The following chapter discuss the results in the appended papers and synthesizes a conceptual framework from them. Section 1.4 offered alternative assumptions for rephrasing the four principal challenges in mechatronic design work, based on the perspectives offered by Type 2 project studies in section 1.3. The alternative assumptions motivated the formulation of this thesis' research questions, based on a desire to explore what Type 2 project studies tend to call "*lived experience*".

Research question 2 (section 1.4) is where the purpose of the thesis and the result of the appended papers meet to address that *lived experience*, with RQ1.1-1.2 being preparatory. The experiential relation between expertise and complexity in mechatronic engineering projects (RQ2) is where this core meeting takes place and where the synthesis of the results can coalesce to answer it.

The synthesis will proceed by the stepwise construction of the full framework from the bottom up, with one figure (figs. 3-7) for each step: First, it will discuss the position established by papers 1 and 2, forming the base of the framework. Second, from that base it will discuss how the results answers research question 1.1. about the experience of expertise. Third, it will do the same for question 1.2. regarding complexity, thus having constructed a micro/meso-view of subjective expertise and complexity. Fifth, the framework will present ITPM as a theorizing lens to make the relation between engineering expertise and project complexity visible through conceptual metaphor, thus answering RQ2. Specifically, how that relation is one of delicate experiential tension. For the more "top to bottom" oriented-reader, the full framework can be found in Figure 9. However, following the bottom-up approach in 5.2-5.4 is recommended for comprehension.

5.1 MOTIVATING THE FRAMEWORK

Before the synthesis can start, the framework must be motivated to address three areas of concern: the purpose of the thesis and the interests of the respective research fields of mechatronics and projects. Constructing a framework using ITPM to afford a micro/meso embodied realist perspective on subjective experience in mechatronic project work has the following potential benefits.

1. **Thesis purpose:**
    a. The framework is *fit for the thesis purpose* due to the concept of embodied metaphor being fundamentally constitutive of the mechanics of perceiving abstract phenomena,
    b. By taking a fundamentally orthogonal view to the positivist and rationalist one of the engineering design research field, the framework directly aims to address gaps of how mechatronics understands its own challenges.
2. **Mechatronics:**
    a. The framework addresses the need for a structured theoretical scaffolding to address the four fundamental challenges of mechatronic design identified in the introduction.
    b. The framework can be used to explicate code-clashes (see section 5.3 in Paper 4) in perceiving legitimate bases of expertise for students and early-career engineers as it creates a base for explaining how certain metaphor-structures can hinder or enable such code-clashes.
3. **Type 2 Project Studies:**
    a. The framework specifically targets the lived experience of project participants,
    b. That the framework is theoretically sensitized to project context through the *loosely-coupled* discursive stance towards defining the primary context.
    c. That the framework is empirically sensitive to project context due to metaphor always being particular in its activation.

5.2 CONSTRUCTING THE FRAMEWORK BASE

The purpose of the thesis, to address the four core challenges of mechatronic work, motivates the following positional base built from the work of the first two papers. As established in the introduction, the mechatronic challenges necessitate a specific organizing perspective, Type 2 Project Studies, focused on the micro- or meso-level of project work in the context of mechatronics.

5.2.1 A ***Grand*** and ***loosely-coupled*** discursive stance

The positional base address Mechatronics' challenges on the basis of the alternative assumptions offered in the introduction by taking a discursive stance towards definitions of mechatronics. The reason for using discourse here, in an mechatronic engineering context, is that it crucially precedes any and all arguments around right and wrong or good and bad: To describe a discourse is to, as far as possible, strive for a reflexive description of a socially evolved and evolving syntax (Alvesson & Sköldberg, 2009, p. 232), where inconsistencies and contradictions in language use are central features rather than flaws. The usefulness of discourse analysis in engineering is not new (e.g. Akeel & Bell, 2013). In addition to how paper 2 affords such a stance through its cyclical framing of mechatronics definitions (figure 2 in paper 2), some more detail on taking Alvesson and Karreman's (2000) typology of discourses is needed. Specifically on the applicability of *Grand* and *loosely-coupled* views for the framework's positional base. In general, a *Grand* view on discourse means "*a collection of discourses, presented as an integrated frame*" (Alvesson & Karreman, 2000, p. 1133), as done in figure 2 in paper 2. A *loosely-coupled* view on discourse generally means seeing language use as being largely *autonomous* from enduring interior meanings/emotions/thoughts, not seeing words used as strictly causing or even necessarily relating to such interior arrangements as dispositions, feelings, or thoughts (Alvesson & Karreman, 2000, pp. 1131-1132).

The *Grand* part of the discursive frame is useful because it zooms out far enough to take mechatronics as a total concept as its context. Instead of simply focussing on, for example, mechatronics' educational practice in a single university or mechatronic industrial practice in a single nation. The scale here implies a trade-off for the thesis: in using the *Grand* stance when framing mechatronics, while at the same time being interested in micro/meso-level phenomena in mechatronics project work, the thesis trades some rigor for relevance (Alvesson & Karreman, 2000, p. 1134). If the thesis from the start had taken a lower-level interest in mechatronics as a context (all the way from global to continent to country to specific organization) it could have produced rigorous knowledge of little relevance. This rhymes poorly with the sensibilities of the core audience for the thesis, which is mechatronics research and project research, the specific sub-audiences in both fields being interested in pragmatic knowledge creation balancing rigor and relevance.

The *loosely-coupled* part is perhaps even more crucial, because it addresses a reasonable theoretical concern between the thesis' use of discourse and metaphor: usually research taking discursive views on the social world (e.g., post-structuralism) often reduce meaning in it to pure language (*discourse determination*) with no room for other ways of seeing (such as metaphor). With this more careful and tentative approach, seeing discourse as loosely coupled to meaning (*discourse autonomy*) in the social world not only allows for conceptual metaphor, but connects to it without subsuming it. What that means for the thesis is that it maintains the multiple-view perspective of the Type 2 Project Studies context, seeing both how team members in mechatronic development projects *talk together* (discourse/meso-level) and how they *understand individually* (metaphor/micro-level) as constitutive of the lived experience of mechatronic project work.

Furthermore, the loose coupling between discourse and metaphor additionally opens up a way to understand potential mechanisms for engineering expertise: Taking the *Grand loosely-coupled* view on mechatronics actors in the mechatronic definitions model sees expertise in "R*ather than the discourse driven subject* [i.e. mechatronics team member]*, the subject may be a politically conscious language user, telling the right kind of stories to the right kind of audience at the right time"* (Alvesson & Karreman, 2000). This maps well onto the picture of engineering expertise painted in chapter 2.2. Through Alvesson and Karreman's discourse dimensions expertise can thus be seen when a "conscious user" of discourse (i.e., the specific language representing the current legitimate basis for practice) can disengage from internal understanding (prevailing conceptual metaphors of practice) and engage with a different meso-level understanding when switching context. For example, when needing to take a critical and costly discovery upwards to the "*right audience*" at the "*right time*", telling the "*right stories*" (e.g., right level of detail and focus) about the discovery and what to do about it.

Therefore, in taking this perspective the positional base affords the framework the open and dynamic stance towards language (discourse) and understanding (metaphor) that the mechatronic challenges need. The discursive model of mechatronics developed in Paper 2 thus forms the frame of the positional base in two ways. First, by describing mechatronics as the empirical setting of the thesis. Second, by establishing its ontological stance as social realist instead of post-structuralist by virtue of it being *loosely-coupled*, and embodied realist by virtue of its use of embodied metaphor. Both ontological stances are commensurate as the framework recognizes the existence of external social reality (social realism), but that empirical access to it is limited to the cognitive faculties of separate bodies (embodied realism). This constitutes the basis for understanding definitions of mechatronics as a kind of constrained ongoing action of individual stakeholders (subjective definitions) or teams (inter-subjective definitions), rather than a global parallel iterative process of increasing correspondence to an idealized "ground truth" of mechatronics (Figure 3). Considering that over the half-century of mechatronic history and literature, which includes many seminal papers, has been concerned with the back-and-forth on the global identity and uniqueness of mechatronics, this could serve as a small but welcome corrective for avoiding unproductive debate (Auslander, 1996; Bradley, 2004, 2010; Buur, 1990; Fumio Harashima, Masayoshi Tomizuka, & Toshio Fukuda, 1996; Hehenberger & Bradley, 2016; Janschek, 2012; Milecki, 2015; Millbank, 1994; Mørkeberg Torry-Smith et al., 2012; Salminen & Verho, 1989; Wikander, Torngren, & Hanson, 2001).

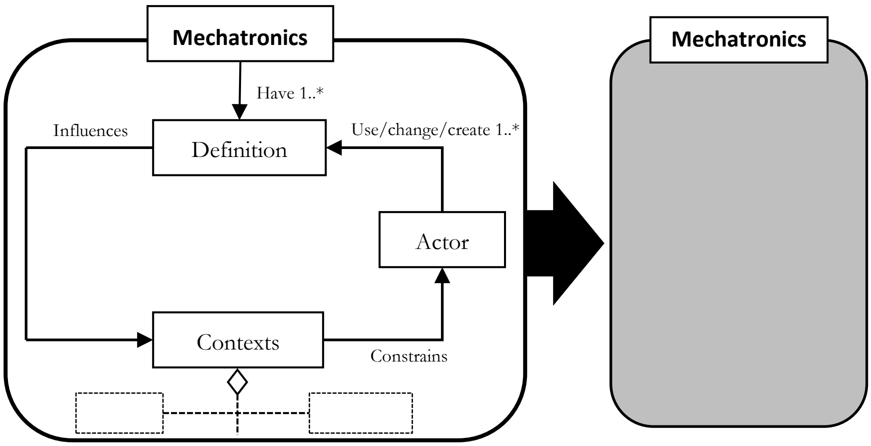


Figure 3: A discursive view of Mechatronics as a foundation for the framework

Simply put, this thesis sees the true identity of mechatronics as pragmatically being what it needs to be at the specific time and place where that need is felt, echoing Bradley (2010). This particularizing feature of the ontological stance of the thesis helps to explain why the core needs/challenges of mechatronics appear generic in their formulation, apart from the lack of foundational theory explaining those needs.

5.2.2 A Type 2 project organizing focus

Having established the base's discursive framing of mechatronics as the foundational context for the framework, the positional base establishes a Type 2 project organizing focus for this framing by integrating the inclusive concept model of mechatronic design research and project management developed in paper 1. A second nested context is thus introduced which increases the focus from mechatronics to mechatronic project work (see Figure 4). In so doing, the second context of project organizing supports the initial discursive framing of mechatronics: by legitimizing perspectives which are useful to answer the RQ, on the basis of the alternative assumptions. Enough is still common between the two fields in the overlapping part of the comparative conceptual model to allow for outlying but useful concepts.

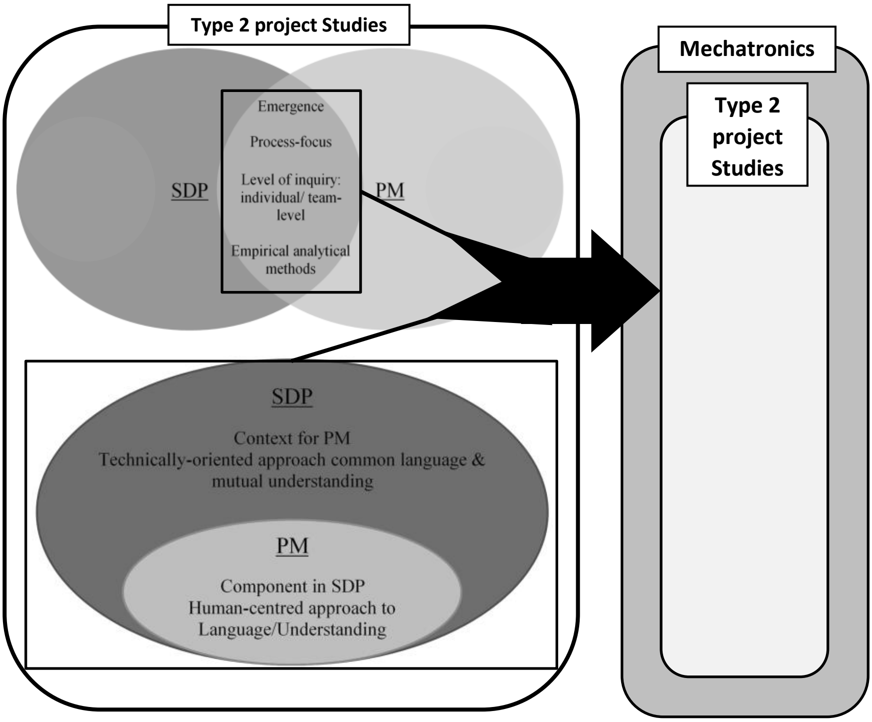


Figure 4: The inclusive and overlapping concept models enter the framework's positional base

The integration of project work perspectives is performed in three ways: First, that Type 2 project studies fundamentally motivates the framework to specifically target the lived experience of project participants (Geraldi & Söderlund, 2016, 2018) as a core unit of analysis. This supports an *analytical interest* in the possibility of empirical material to speak to RQ1.1 and RQ1.2: how complexity and expertise are subjectively experienced. Second, this type of project research brings in and motivates more interpretative methods on qualitative data. These support a broader understanding of the problems, but still standing on the shared methodological base of both fields being process-focused, empirically interested in the level of individual/team, and recognizing emergence of both technical and social system properties and behaviours. Third, a reflexive stance is afforded towards the challenged mechatronics assumption and value of *unity* in design methods, development processes, and common language. The utility of a reflexive stance can facilitate more nuanced appraisals of long-standing mechatronic norms (including its assumptions and values), leading to a broader understanding of how expertise and complexity are experienced in mechatronic project contexts. Such reflexivity enables the alternative assumptions offered instead of the prevailing *unity*-perspective, providing a more diverse view of inconsistencies and contradictions in mechatronic project work which traditionally has been reduced to features of problems or problem-spaces.

5.3 COMPLEXITY AND EXPERTISE

The two phenomena of *Complexity* and *Expertise* form the core empirical structure of the framework. The positional base established above serves as a logic for the centrality of these two concepts. Complexity was described as "*a generic problem*" by Mørkeberg Torry-Smith et al. (2012, (S) in table 1) as a generalizing final mechatronic challenge. However, if constructing a framework for addressing mechatronic challenges through a human-centred micro/meso-level approach to understanding and language (discourse), then the *experience* of complexity in mechatronics is not a *generic* problem. Similar to how paper 4 challenged the universality-view of professional skills for expertise, the framework refutes such a generic view on both ontological and empirical grounds: from both a micro and meso perspective, in any specific mechatronic development project, complexity is necessarily extremely particular. In both how complexity is experienced in the project by individual members as well as by the team as a group. Expertise, in turn, is likewise constituted.

5.3.1 Expertise

The framework is afforded a view of expertise based on the theoretical frame in 2.2 and through three crucial components based on the work in the fourth paper. These three components (see Figure 5) are: First, the causal chain of expertise in mechatronic project work; Second, to how a team-member relate to their knowledge; and third, to what extent a team-member understands to what extent facts are context-dependent and complex.

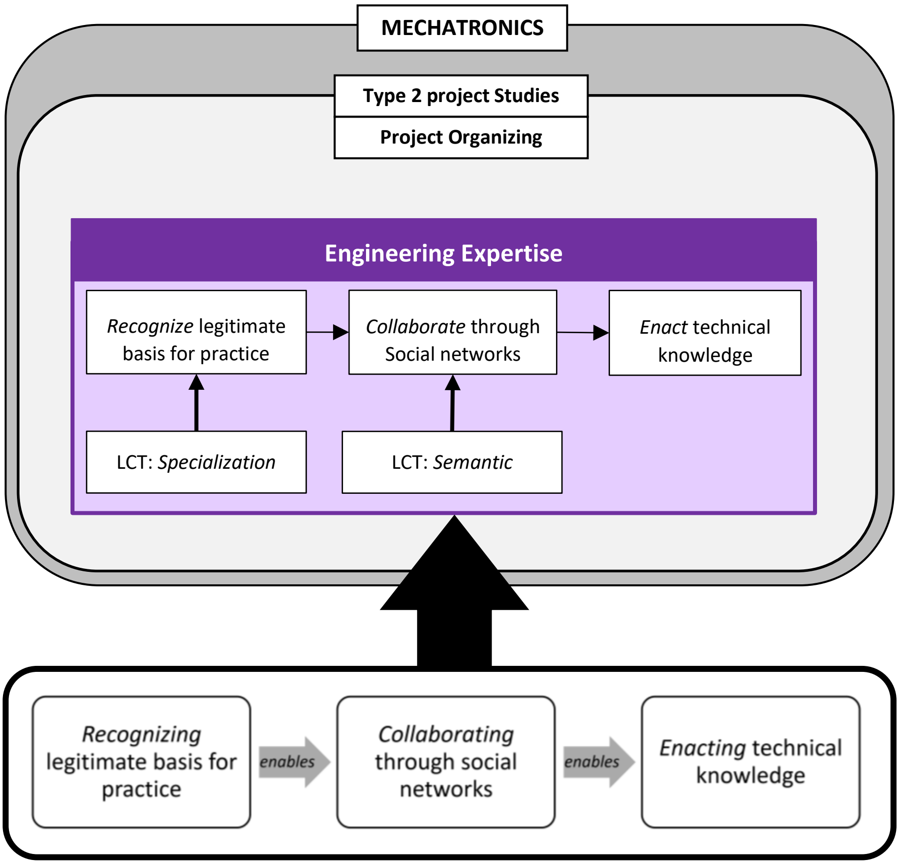


Figure 5: Expertise enters the framework

First, a three-part model of engineering expertise (fig. 5). The model pertains equally to mechatronics engineers and project members organizing activities of the project, which includes but is not limited to the project manager or team lead. The model argues that expertise constitutes an ability to enact technical knowledge, through social networks of professional actors, by continually recognizing the present legitimate basis for practice. These three parts are causally connected: Understanding what kind of practice (language, behaviour, and level of detail) which is legitimate (1) in any given situation enables collaboration (2) in networks, which in turn enables the enactment of technical knowledge (3). Please see chapter 2.1-2.2 in paper 4 which establishes a logic for this view of expertise and further explains it.

Second, the LCT *Specialization Dimension* which "*explores the basis of achievement underlying practices, dispositions and contexts*" (Maton, 2014, p. 30). It sees knowledge-knower structures as constitutive of practices. *Specialization* gives the framework a way to map out the importance of knower and/or knowledge in situations of mechatronic project work, which is crucial for seeing what the present legitimate basis for that work is like.

Third, the LCT *Semantic Dimension* represents how context-dependent and complex the meanings of legitimate facts are in experiences of mechatronic project work. This dimension carries increased importance for the framework compared to the role it played in paper 4, since it connects to *perceived complexity*: In mechatronic project work specifically (Wolff, 2018), the semantic structure of facts about systems and processes is commonly *context-dependent* (SG+) and *complex* (SD+), indicating *worldly codes*. High degrees of semantic density (SD+, i.e., complexity) seem to associate with both the ability to recognize and to collaborate within legitimate basis for practice. Furthermore, Paper 4 found that code-clash due to rationality bias seemed to mediate this connection (see section 6.1 in Paper 4).

5.3.2 Complexity

In the thesis' dual context of mechatronic project work, complexity is based on the perceived complexity-view of Mikkelsen (2020b), positioned between ideal type 4 and 5 of project complexity research (Mikkelsen, 2000a). The empirical findings of the case study (in papers 3 and 5) specify the role of perceived complexity in the dual context of the framework, having three crucial characteristics pertinent to answering RQ1.2 on how complexity is experienced in mechatronic project work.

First, the emergent themes were identified as generally descriptive of how complexity was perceived. These themes painted a generalized picture of lived project complexity in mechatronics that resonated with the literature generally (Christian & Eklund, 2015; Hillmer, 2009; Mikkelsen, 2020b) and specifically with four of the mechatronic challenges from Tory-Smith (2012), see section A, chapter V, in Paper 3. From the general to the more specific, the further work on the case study data in Paper 5 elicited a more theoretically grounded and granular view of complexity, identifying *Autonomy*, *Connectivity*, and *Diversity* as important complexity dimensions (see figure 5 in Paper 5) connected to internal and external drivers of complexity in the project through high-ranking factors (Bakhshi et al., 2016). Paper 5 also established the value of seeing complexity in mechatronic practice as crucially perceived rather than objective.

Second, the case study found that, from a practice perspective, size is an underlying logic for this perceiving of complexity. Stemming from a general tendency (e.g. Sinha & de Weck, 2016) towards perceiving complexity as structural (Mikkelsen, 2020), which in turn rests upon a historical predisposition towards structuralist understandings of knowledge in engineering practices (Hyldgaard Christensen, 2015, chapter 7). This includes a structuralist understanding of behaviour, since "behaviour" is relations and connections between separated parts in the structuralist view (e.g. in Gero's FBS). Valid arguments such as Törngren & Sellgren (2018, p.495) "*it is not given that geometrical representations adequately represents behavioural models*", while indeed correct, are interior deliberations on complexity frameworks (CPS in this case) and does not pertain to underlying logics of complexity. Indeed, the structuralist stance is so common as a tendency due to the universal experience of associating early interactions with complex objects and their structure, leading to the subjective judgement that abstract unifying relationships (i.e. organization) *is* physical structure (George Lakoff & Johnson, 1999, p. 51). In paper 5, the three complexity dimensions found in the case where not directly related to a structuralist notion of size (which would be covered by the dimension of *Size* in Bakhshi et al. (2016)), but still size was found to underlie actual complexity perceptions. So while this is a general feature of engineering practice (Hyldgaard Christensen, 2015, p. 20, chapter 1), mechatronic projects commonly exhibit such structuralist size-oriented perceptions of complexity as well (Bradley, 2010). But what about when the mechatronic project is considered "small"?

Third, the critical case study results support theoretical generalization of its view of complexity, due to selecting a critical case (see chapter 3.1. in paper 5). This serves both the framework as a whole, and to answer RQ1.2 in particular, because it supports the theoretical extension of the mechatronic-specific conception of perceived complexity: *Even if a mechatronic project has limited ostensive organizational size and low apparent technological novelty and complicatedness it will (or can) still be perceived as complex*. This view goes against the common portrayal of project complexity frameworks (see chapter 2.4.1 in paper 5) and posits size as a both a part of complexity topologies but also fundamental to its structuralist perception.

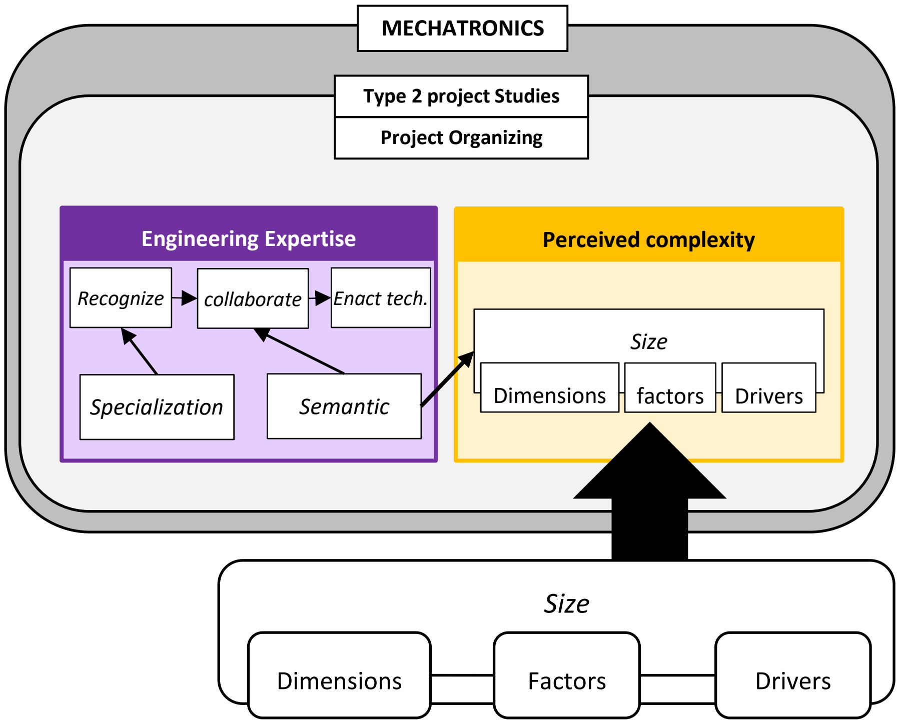


Figure 6: Perceived complexity enters the framework

The framework can help seeing why this might be so in specific relations between how complexity and expertise are perceived. Apparent limited technical novelty/complicatedness might make the micro-level perceptions (individual understanding) of system-specific complexity low, and individual team-members might experience ease in formulating potential solutions for themselves. However, micro-level perceptions of low technical (i.e. structural/size-related complexity) complexity does not imply ease outside of this internal solution formulation. Indeed, on the evidence found for *rationality bias* amongst misaligned mechatronics engineers in paper 4, a misperception of low *semantic density* (i.e. low complexity in meanings of facts) as low *semantic gravity* (i.e. meanings of facts are context-independent) can hinder expertise. Therefore, the results from paper 4 understood through LCT's *Semantics Dimension* (Maton, 2016), connect expertise to perceived complexity in the framework through the complex and context-dependent nature of facts (*Semantics*) in mechatronics project work (Figure 6).

5.4 CONCEPTUAL METAPHOR

Conceptual metaphor is the final piece of the framework. The aptness of ITPM for the thesis aim and framework was theoretically motivated in chapter 2.3.2 and the empirical consequences of its use to theorizing perceived complexity was detailed in chapter 5.2. in paper 4. These will not be repeated here. An additional point about theoretical balance must be made however.

The use of embodied conceptual metaphor balances the discursive stance in the micro/meso-level interest of the framework: The discursive stance serves meso-level better than the micro-level since "*The capacity of language to represent non-trivial conditions and interior arrangements are limited.*" Alvesson and Sköldberg (2009, p. 234). Non-trivial interior arrangements (i.e. complex abstract concepts) are exactly what ITPM has the capacity to represent, through its four integrated theories. Thus, complexity-perception is both discursive on the meso/team-level and cognitive/metaphoric on the interior/individual-level. It shows itself in observed *discourse* of the patterns and norms of the mechatronic development team's shop-talk. It shows itself in the concomitantly activated *conceptual metaphor,* inferred from situations in the case study (e.g. "*That meeting was heavy*", "*he was a CAD-database"*) and from the bias themes identified in the survey-study (e.g. rationality bias in perceiving data to have inherent meaning, indicating metaphorical structure).

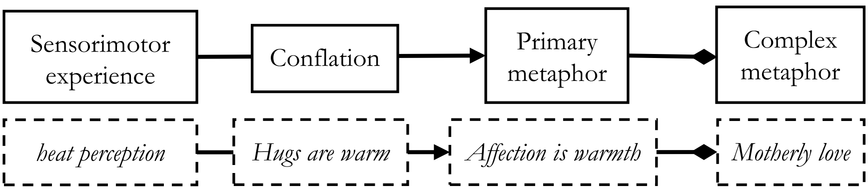


Figure 7: How physical experience form abstract concepts (with example: heat to motherly love)

Metaphor is constituted in the framework in three parts (see Figure 8). First, ITPM includes one or more primary metaphor as the "atoms that form molecules" (George Lakoff & Johnson, 1999, p. 74) of complex metaphor (Figure 7). Second, abstract concepts are constituted by one or more complex metaphors. Third, the specific complex metaphor *Complexities are Big Burdening Physical Structures* found in the case study is introduced as *one potential* complex metaphor able to constitute the abstract concept of *complexity*. It serves as apt for the common mechatronic development context related to size discussed in paper 4.

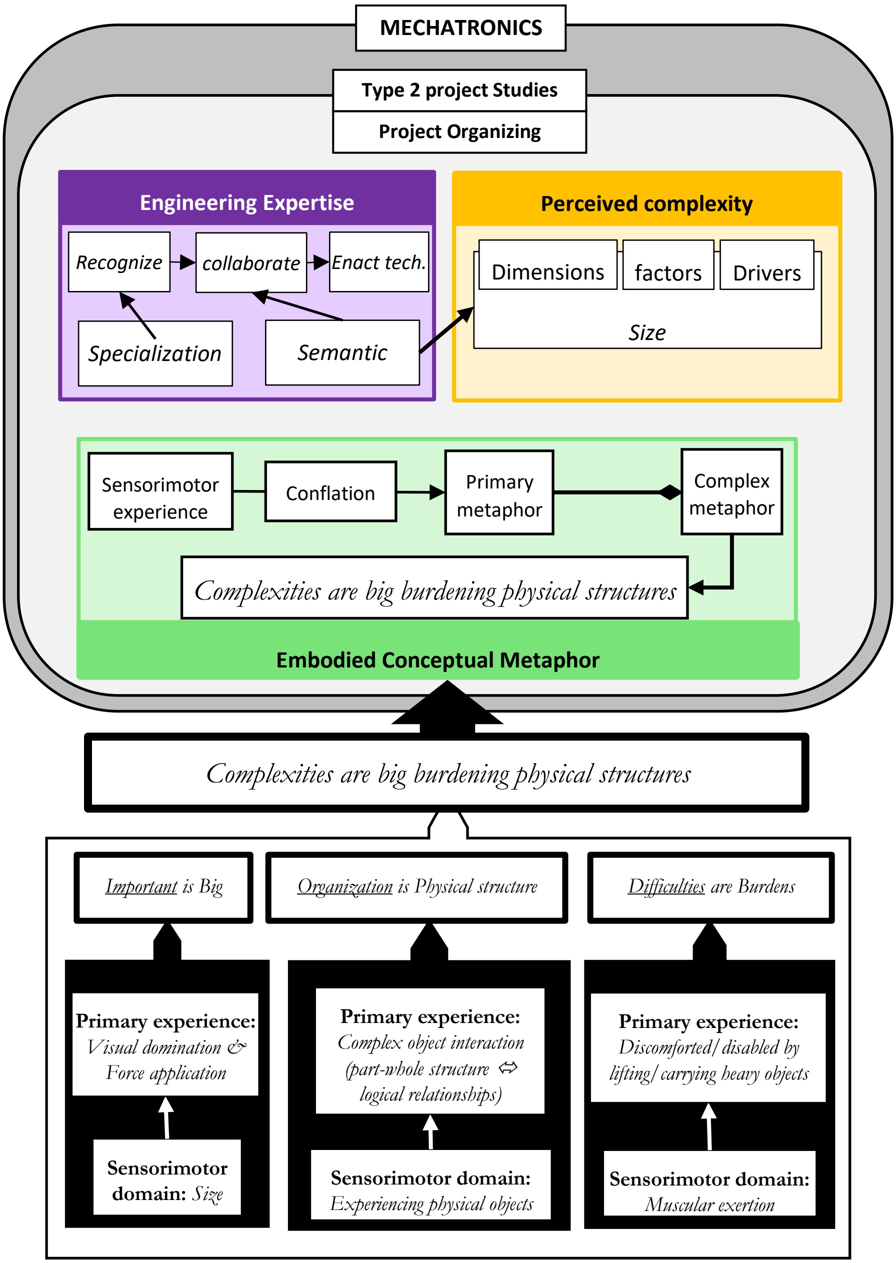


Figure 8: ITPM enters the framework

5.5 THE FULL FRAMEWORK

Now the framework comes into full view to answer the second research question as to what constitutes the experiential relation between expertise and complexity in mechatronic project work. The framework (Figure 9) visualizes the respective works on engineering expertise that answers RQ1.1 and on perceived complexity which answers RQ.1.2. The lens provided by embodied conceptual metaphor on micro-level phenomena enables the framework to answer RQ2. Remember that without embodied metaphor, the relation between expertise and complexity is tenuous and unclear, consisting of a general connection between two observed phenomena (*semantic code-clash ⇔ perceived complexity in the autonomy, connectivity, and diversity dimensions*) seen through theories that are primarily apt for the meso-level, that is, LCT and the *Grand* discursive stance. But since the view taken on meso-level shop-talk and understanding is *loosely-coupled* in addition to *Grand*, the discursive view allows equal space for ITPM to give access to the interiority of team-members lived experience. This will enable a more interesting and granular answer to RQ2 than just stating: *if the team-member is competent in the three-part manner described by the framework they will avoid misaligning their expertise due to bias, and thus lowering their perceived complexity by virtue of maintaining legitimate semantic codes.* This is not enough.

I will first explain *how* embodied metaphor answers RQ2, using the complex metaphor elicited from the case study as a context-appropriate example. Further examples will mostly come from my data. Then a few other approaches to explaining the experiential relation expertise-complexity follow.

The causal structure offered in the end of paper 5 gave the *Complexities are Big Burdening Physical Structures* as a novel metaphor for perceived complexity. It maps team-members direct lived experience in mechatronic project work to their abstract conceptual perception of project complexity. This novel complex metaphor is one of many possible metaphors for complexity, but paper 5 left the connection to expertise and competence tentative in chapter 5.2. Picking up from where, the novel metaphor serves the framework as a context-appropriate example of how mechatronics engineer internally experience the tension between their own expertise and seen complexity: Through common primary metaphors (George Lakoff & Johnson, 1999, pp. 50-51), it conflates (➔) <u>sensorimotor experiences</u> with more *abstract concepts*:

- <u>size</u> ➔ *Importance*;
- <u>muscular exertion</u> ➔ *Difficulties*;
- (experiencing/sensing several) <u>physical objects</u> ➔ *Organization*.

The three primary metaphors integrate through conceptual blending (Fauconnier & Turner, 1998, 2011): *Big* + *Burdening* + *Physical Structures* ➔ *Complexity*. The three primary metaphors activated together entails a specific range of project complexity to be perceivable through the complex metaphor. The three examples below illustrate how this happens in the framework.

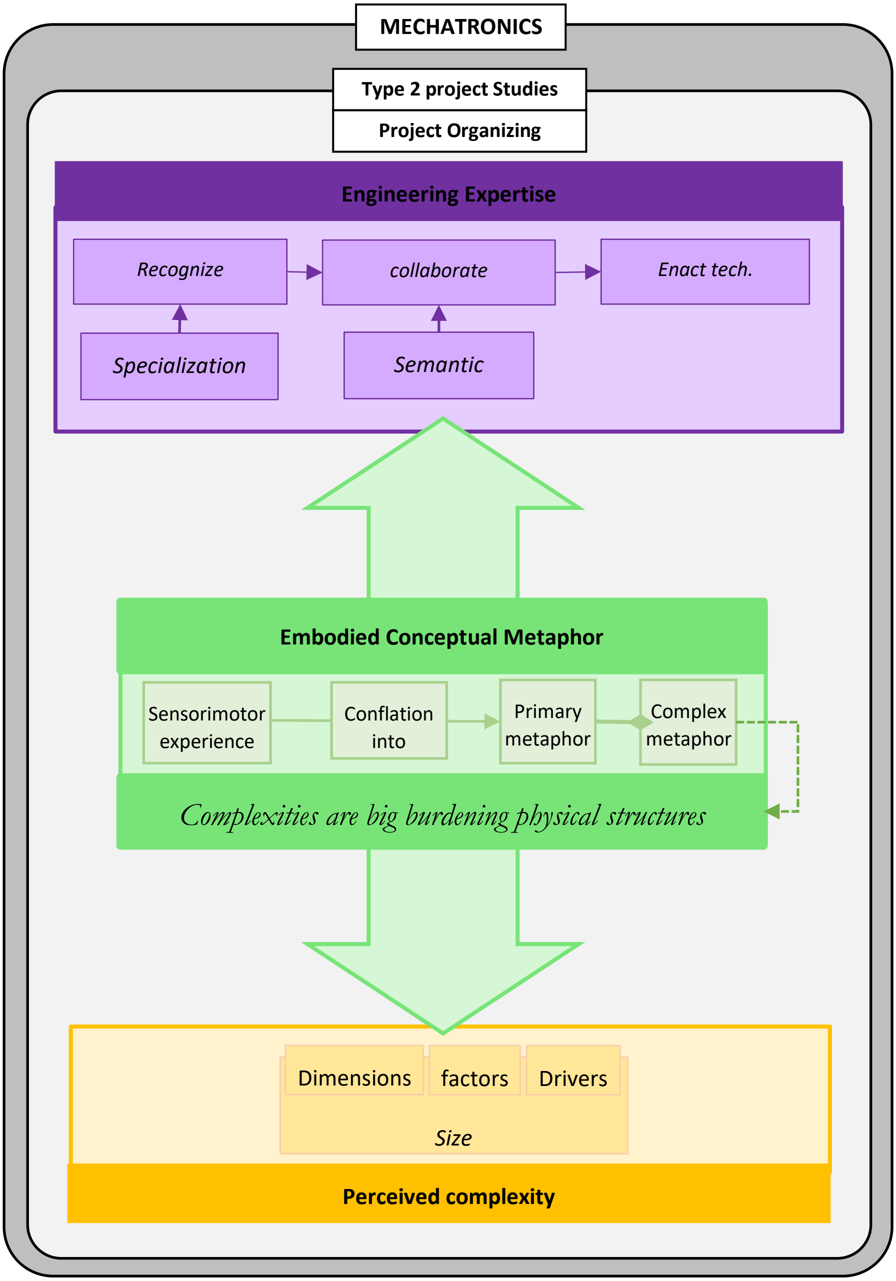
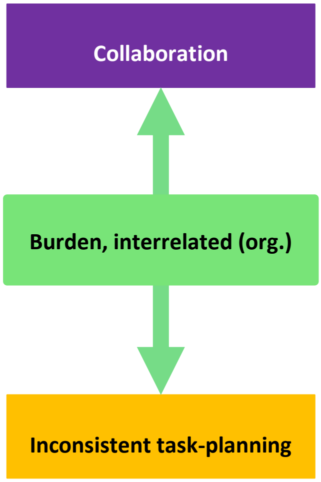


Figure 9: The full framework

5.5.1 Metaphors instantiates expertise-complexity relations

Example 1

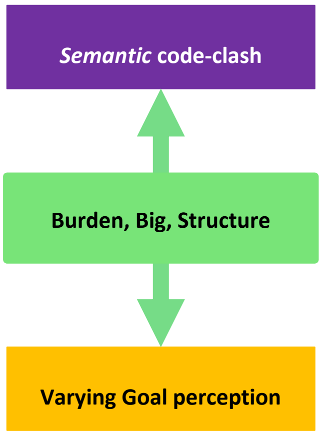
In an observation of a daily standing meeting a specific backlog was opened that had long been neglected. There were only 4 people standing very close to a big 50-inch TV monitor, higher than the team members. Many heavily inter-related task entries where in the stack visualized in the task management system on screen. There was a silence and a simultaneous visible squaring of shoulders. In a later interview, one of the members confirmed the interpretation, sighed and looked away: "*It's always like this, I'm the bottleneck, I don't have time*"



The pre-linguistic activation of all three constitutive primary metaphors was directly observed in the squared shoulders of all the participants: visibly *burdened* by the *big* and *tightly linked* list on the *big* monitor. The meeting contained little direct usage of the word "complexity", but much talk of "difficulty" in relation to the backlog which in project practice settings are epistemologically close (Mikkelsen, 2020b).

Example 2

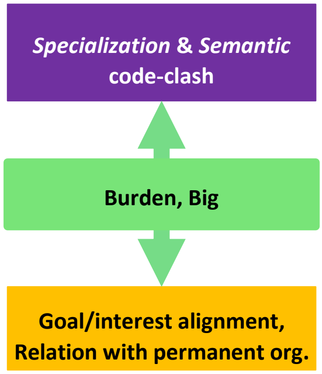
In an observation of a conflict-heavy FMEA meeting in which the team met with an FMEA-engineer from the line-organization, there was a very visible *semantic* code-clash on the complexity of the word "risk" on the part of the team. They also explicitly expressed size-oriented overwhelm from the presentation material on risk-assessment, thus mediating *semantic* code-clash through all three primary metaphors. Interpretations were validated after the chaotic meeting, with for example the project manager sighing and exclaiming "That was *heavy*!" (Difficulties are burdens).



In the end the team chose not to implement FMEA in their project. The risk analysis was required by their formal product development process, but the electronics engineer and mechanical engineer expressed that the formal procedures were "too big and complex for the project" at a later meeting. The software sub-team said nothing, and the PM agreed, visibly physically burdened (because the FMEA was a process-requirement on him from the project office).

<u>Example 3</u>

> In discussing early integration testing of the electronics at an external facility, a team-member said: "I have to spend so much time on politics every day. I tell people, look at these numbers! Is this what the customer wants? I need to struggle every day. But after a while it's too *heavy*, I can't make a 6-month investigation for every argument, its too *big*! Because they just need to say "No, we'll do it like this instead". Where's their goddamn 6-month investigation and data?!"



Here the issue is both recognizing the basis for legitimate practice as well as collaborating on that basis. This resulted in clear code-clashes in both *Specialization* (Knower/Knowledge) and *Semantics* (context-dependence/multi-faceted facts). This was experienced by the electronics engineer through the *big* and *burden* primary metaphors, driving perceived complexity in the *Connectivity* and *Diversity* dimensions (Figure 5 in paper 5). Specifically in the factors of *relations with permanent organization* and *Goal/interest alignment*. It is the perception of complexity in these factors which the physical experience of the primary metaphors constitute.

5.5.2 Constituting the experiential relation: answering RQ2

From the description of the full framework and the examples above, research question 2 is answered thusly: Based on the survey and case study data, analyzed through the selected theories of LCT and ITPM, the experiential relation between Engineering Expertise ⇔ Project Complexity is constituted by embodied conceptual metaphor. The everyday subjective experience of the tension between the two is made objectively real through specific sets of primary metaphors, which in the critical case study in this thesis are *Big Burdening Physical Structures*, and their respective associated sensorimotor domains.

The theoretical generalization of embodied metaphor as being constitutive in the context of mechatronic project work is possible. Note that theoretical generalization, as opposed to statistical generalization, is concerned with the *existence* and *shape* of a phenomena and its environment as opposed to being concerned with direction and effect-size. Any statistical generalization of the thesis results would require arguing for *how much* the proposed novel conceptual metaphor, as a whole and in its parts, mediate "objective" (or more probably self-report measures of) relations between complexity and expertise). As well as in what *direction* between them. On the basis of the work done this is both uninteresting and nonsensical: From the start the thesis neither intends nor supports statistical generalization, since such generalization presupposes strong constructs which in turn necessitates theory development. Which is the purpose of theoretical generalization (Flyvbjerg, 2006; Payne & Williams, 2005; Yin, 2014). The fact that the framework supports the generalization of *size* as an underlying logic for perceiving complexity in mechatronic project work (see 5.3.2) also supports the generalization of the size ➔ *Importance* primary metaphor. It also supports generalization of physical objects ➔ *Organization*, because the conflation of physical structure with abstract structure in this primary metaphor directly relates to core structuralist tendencies reported on for both the perception of complexity (paper 5) as well as expertise (paper 4). Direct support for theoretically generalizing muscular exertion ➔ *Difficulties* was found in the various triangulated observations of expressions of muscular exertion in the data, such as those exemplified above. Does the generalizability of its parts enable generalization of the whole novel metaphor *Complexities are Big Burdening Physical Structures*? Yes, by virtue of the *integrative constitutive* nature of ITPM which gives the "*grounding of the whole is the grounding of its parts*" (George Lakoff & Johnson, 1999, p. 63).

5.5.3 Alternative explanations of the expertise-complexity relation

Team Mental Models and the Distributed Cognition Model are two alternative theories that serve to explain certain aspects of the expertise-complexity relation. The mechatronic engineering practice context necessitates a compacting synergistic integration of development work in tightly integrated multi-disciplinary development teams. For the analysis of the meso-level of the team and interactions therein, both theories can serve well (Giordano, 2002; Mohammed, Ferzandi, & Hamilton, 2010;

Rouse, Cannon-Bowers, & Salas, 1992). They struggle, however, to answer the second research question as posed here due to its micro-level embodied realist concerns (G. Lakoff, 2012). This is also reason to revisit the formulation of the third mechatronic challenge, which stated that it is differing mental models that is one of the most significant problems, however the literature of mental models or team mental models is not related to, explained, or even referenced. As a consequence of this low semantic density, the usage of "mental models" might be a stand-in for any number of vague ideas for how people differ internally. Again, giving the thesis reason to turn towards interiority.

6 CONCLUSION

This chapter concludes the thesis by consolidating its central argument. It presents the contributions to the research field, the practical implications, and suggests potential avenues for future research.

6.1 CONCLUSION

The tensions in mechatronic engineering practice and inside the mechatronic engineer is fascinating. The necessary skillset for the mechatronic engineer in the 21st century has never been more contentious and the complexity they experience in their work has received little support by scientific research in general and mechatronic design research in particular. The reason for this is multi-layered and pertains to the nature of scientific domains and their paradigmatic differences (Bucciarelli & Kuhn, 1997; Davies, Manning, & Söderlund, 2018; Kuhn, 2012).

The thesis started by discussing the implicit assumption of long-held views of what mechatronics *is* and what it *needs* (Hehenberger & Bradley, 2016; Mørkeberg Torry-Smith et al., 2012; Salminen & Verho, 1989; Törngren, Qamar, Biehl, Loiret, & El-Khoury, 2014; Van Der Auweraer, Anthonis, De Bruyne, & Leuridan, 2013)**.** In fundamentally agreeing with Bradley (2010, 2015) in viewing mechatronics from an empirically responsible position of open definitions and a focus on situated practice, we positioned the field of mechatronics in relation to the field of project management which is its historically estranged sibling (Lenfle & Loch, 2011). The thesis argued for taking realism seriously and focussing on the necessarily objective nature of subjective phenomena, necessitating theory that supported the investigation of "*non-trivial interior arrangements*" (Alvesson & Sköldberg, 2009, p. 234), which motivated embodied realism and the cognitive linguistic theory of embodied conceptual metaphor. ITPM, specifically.

Building on an abductive combination of mixed-method studies, the thesis constructed a framework based on this understanding. It argued for the importance of balancing the micro/meso-level aspects of the tension between expertise and complexity in order to understand them in practice. That understanding consisted of embodied metaphor, and a specific novel one was offered to show the structure and mechanism behind perceiving complexity in the context of mechatronic project work.

Having answered the research questions in its parts (RQ1.1&1.2), and as a whole (RQ2), the framework directly addresses the mechatronic challenges based on the offered alternative assumptions. The closed fist around the perceived "lack of common" language and understanding is opened by an empirically responsible and mechatronics-appropriate understanding of the lived experience of project work. Such understanding requires an embodied realist view on the living nature of abstract concepts. This is a personal experience that can only be brought online in everyday work: Understanding the relation between one's own physical sensing and abstract concept by using the framework, and how that relation is closely related to emotions.

6.2 LIMITATIONS

The expected perceived limitations can be formulated as three bulleted strawman-arguments. They will be addressed in the following paragraphs.

- **The scope and its *relevance*,** or
  "*The questions & scope is too broad!*";

- **The *empirical material* in relation to the scope,** or
  "*The empirical data is too weak to support the intended relevance!*";

- **The *intended* contribution in relation to the data,** or
  "*The answers and the contributions are too vague!*".

The limitations of the thesis are largely constituted by the limitations of its parts. Specifically, the issue of different types of generalization and their respective limitations in relation to the choice of a single case study, which was discussed above (5.5.4) in relation to the framework and thesis as a whole, and specifically for the publications in papers 3 and 5. The often misunderstood efficacy and specific utility of single-case study findings have been thoroughly detailed by many researchers, especially Flyvbjerg (2006) and Siggelkow (2007). These authors have effectively posited that the purpose of conducting single case studies is not to establish statistical generalizations, but to provide analytical insights instead (Flyvbjerg, 2006).

A specific limitation concerning the empirical material is the lack of quantitative data on complexity to more strongly characterize it in its context. The limitation was theoretically anticipated in chapter 2.1 by positioning the thesis in-between Type 4 and 5 in Mikkelsen (2020a, table 3)'s typology, indicating a pragmatists stance less interested in the quantitative measurement of objective complexity (i.e. Type 1). Which is at best a precarious (Rolstadås & Schiefloe, 2017; Tarride, 2013) and often criticized (Geraldi & Söderlund, 2016; Mikkelsen, 2020b) endeavour.

However, there is a possible general limitation for the relevance of the theoretical contribution to the mechatronic audience. Such potential limitations were anticipated in the final sixth step of Alvesson and Sandberg (2011, p. 232)'s approach to generating research questions. The initial assessment was that, based on the theoretical choices of a Type 2 project organizing viewpoint, the offered alternative assumptions still held the same fundamental concern inherent to the *unity* assumption on which the four main mechatronic challenges' where based:

Increasing the efficacy, efficiency, and productivity of engineers, individuals and teams.

Does the framework, as the contribution of the thesis, achieve this initial assessment? In the introduction I started from the core for engineering, that of productivity. I explained how an organizing-perspective was needed, based on a historical account of mechatronics engineering and its challenges. The concern with the needs of the field never left, and stands behind the micro-level interest in the interior arrangement of concepts inside engineers. A lack of relevance can only stem from alienation due to the unfamiliar selection and combination of theories and their analytical entailments for the data, or from a lack of perceived utility of the results. The first has been mitigated by motivating the relevance of the theory choice for the stated purpose and posed questions throughout the thesis. The second will be addressed below.

6.3 IMPLICATIONS AND CONTRIBUTIONS

In what way is this a *mechatronic* thesis and how does it contribute to mechatronic design research? A thesis should never try to be any specific kind other than what is motivated by its purpose, oriented by its theoretical underpinnings, and directed by its research questions. That being said, the thesis fiercely guards its primary empirical and research-disciplinary context of mechatronics. The strongest reason for which is that it took as its purpose to treat those challenges which its discipline for good reason has been historically ill disposed to address, *but on the same logic as they were posed*. If the thesis had simply taken mechatronics as an arbitrary engineering design context because one is empirically needed and theoretically motivated by such positions as Type 2 project studies, it would have impoverished the thesis. Many choices concerning the selection and treatment of data would have missed the "mechatronic component", such as focussing on investigating the role of development environments and CAD and part databases for understanding mechatronic project environments (In observations, interviews, and directly).

Taken together, the conducted research gives reason to free both mechatronic practitioners and researchers from the assumption of *unity* in a way that does not throw the baby out with the bathwater. It contributes to *Mechatronic design project practice* by removing the expectations and valuation of unity as naturalized without throwing out efforts to create consensus and move development work forward. A more realistic and pragmatist stance which realizes and makes non-personal the mechanics of competence and complexity serves to open up for real discussion. Or even better, real shop-talk. The utility of the framework is primarily for promoting one's own understanding of the micro-level internal mechanisms in one's mind *and other's minds*. It serves, essentially, the same type of role as the V-model: a "*reminder model that guide us to less perilous paths when developing solutions to problems*" (Mooz & Forsberg, 2006, p. 1368) which in the case of the V-model focuses on pairing decomposition with testing and in the case of this thesis focus on pairing expertise with complexity through ITPM.

The thesis contributes to *project studies research*. This thesis included the field of project studies on the basis of what it could offer in terms of perspective, while promising to deliver what project studies have been calling for: a focus on "lived experience" in project. The thesis took this call more literally and seriously than commonly held in taking both words (*lived* and *experience*) as central for its theoretical positioning in an embodied realist understanding of the living underpinnings of organizing work on a specific (mechatronics) context. "Specific context", incidentally, being the other major call of project studies.

The education of future mechatronic engineers is an important facet of mechatronics research as well as the practice of its education. Also relevant for Engineering Education in general, the thesis broadens the invitation from the concluding remarks in the fourth paper to educators to strengthen attitude change strategies for professional skills, not only through understanding codes and code-shifting behaviours in and for students. But also to finding ways to show and motivate understanding engineering practice through an explanation of the micro-level represented by conceptual metaphor and the meso-level represented by legitimation codes. Doing so could give early engineers an edge in their core activity of problem-solving, as was found by Wolff (2018, p. 192) in practicing engineers (on the meso-level), if they can leverage this conceptual understanding into their practice. Such leveraging of conceptual understanding should be expected to hinge on appropriate metaphoric cognition (Gibbs, 2013; G. Lakoff, 2014).

6.4 FUTURE RESEARCH

A potential approach to continue the work started in paper 2 can be to take a higher-level interest in potential macro-level metaphors of mechatronics. As Bradley (2010) asked: "*For instance, is there, or indeed could there be, a single overarching structure for mechatronics, or are there several interrelated and interlinked structures, each emphasising a specific aspect of the whole*". It is exactly questions like this that ITPM can serve to help answer, to find and detail empirically the objective existence of such conceptual structures out in the wild, so to speak (i.e., in the brains of engineers).

It might also be interesting to go the other way and investigate micro-level aspects of specific types of instances of single mechatronic challenges. Such micro-efforts might complement higher-level efforts to understand specific design-situations, such as the research in Team Mental Models or Distributed Cognition (Gasson, 2005; Giordano, 2002; Mohammed et al., 2010; Rouse et al., 1992; Stingl & Geraldi, 2017; Subrahmanian et al., 2003).

Further interest can be taken to investigate broader conceptions of engineering expertise through ITPM. The work in the thesis was not amenable directly to in-depth micro-level investigations of expertise isolated from the broader framework. This was a natural consequence of the abductive reasoning process (Figure 2) which posited the empirical investigation of expertise as deductive and oriented towards statistical hypothesis testing of an expertise-construct. This is not appropriate for metaphoric elicitation for the same reason as those given in chapter 3.1.1. But as a next step, a future study can well develop the framework further to increase the micro-level detail of expertise.

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