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Design Automation Systems for the Product Development Process: Reflections from Five Industrial Case Studies

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Abstract

This paper presents five industrial cases where design automation (DA) systems supported by design optimization has been developed, and aims to summarize the lesson learned and identify needs for future development of such projects. By mapping the challenges during development and deployment of the systems, common issues were found in technical areas such as model integration and organizational areas such as knowledge transfer. The latter can be seen as a two-layered design paradox; one for the product that the DA system is developed for, and one for the development of the DA system.

Keywords: design automation, multi-/cross-/trans-disciplinary approaches, design optimisation

1. Introduction

Industrial product development processes are often iterative, with numerous interdependent and repetitive sub-processes. A common way of rationalizing the product development process (PDP) is by introducing design automation (DA) systems supported by design optimization (DO) to support parts of the process. DA can serve as means to automate repetitive and manual activities of the design process, such as producing variations of CAD models, while DO is a means to further automate the design process by letting an optimization algorithm autonomously search for solutions that maximize or minimise a prescribed goal function. Hence DO can be seen as way to mimic the iterative and incremental change process usually carried out manually by cooperating teams of engineers.

The main scope of this paper is to broaden the general understanding of DA systems and to further increase the available empiric data of applied DA and DO cases in industry. This is done by outlining five different industrial cases, as well as by finding their commonalities and differences. While there are works mapping the different available technologies onto different stages of the PDP (e.g. Rigger et al., 2018), more light can be shed onto the issues associated with the *realization* of DA applications. Such an overview would aid future development by supplying more information about the traits of previously carried out projects. Since none of the studied cases has been carried out without obstacles, the cases give an opportunity to draw conclusions on recurring challenges that needs to be handled in future development processes. As a result, the work summaries issues which has the potential of becoming topics for further research.

This paper covers the application of design automation (DA) and design optimization (DO) applied to five industrial cases of different character, as well as the lessons learned from developing these solutions. The paper starts with a theoretical overview of methods and tools used during the case studies. This is followed by a description of five specific cases which are classified based on where in PDP the solution is applied, which methods that are used, and how they are implemented. Using this data, the inferences made and the implications of introducing DA systems into the PDP are discussed.

Furthermore, these findings are used to point out the trajectory for future development of DA systems. Finally, the paper is wrapped up with the conclusions drawn.

2. Frame of reference

A generic product development process (PDP) contains a set of phases, where the design of a product is considered conceptual and later detailed prior to production, where each phase often runs in iterations (Ulrich and Eppinger, 2016). Within these phases various tools and techniques are utilized in order to acquire knowledge about the design of the product or component. The accumulation of knowledge with time creates what is known as *the design paradox* (Ullman, 2010), which describes the lack of knowledge in the early stages of the design process, where there is still room for making changes in the design. Later, once the knowledge is acquired, the room of making changes has shrunk and the costs of those changes have exponentially increased. Software and tools supporting the PDP constantly need to evolve as new technology is being developed and introduced and market demands are increasing. Amongst those tools are design automation and design optimization, introduced in the following subsections. Such tools in turn pave the way for increased customization of products – an important strategy for maintained competitiveness in certain business fields (Blecker and Abdelkafi, 2006).

2.1. Design automation

As many engineering design activities are of repetitive and tedious nature, they are subject for automation. Design automation is defined by Cederfelt and Elgh (2005) as:

> *"...engineering IT-support by implementation of information and knowledge in solutions, tools, or systems, that are pre-planned for reuse and support the progress of the design process. The scope of the definition encompasses computerised automation of tasks that directly or indirectly are related to the design process in the range of individual components to complete products."*

Knowledge needing to be formalized is a central element of design automation, which may be the reason of the strong commonalities of design automation and knowledge-based engineering (KBE). According to some (Kuhn et al., 2012; La Rocca, 2012) KBE are systems that connect knowledge-based systems and CAD while other (MOKA Consortium, 2001) includes all activities involving automatic knowledge handling in engineering design. Rigger et al. (2018) divides a DA system into inputs, outputs, goals, and DA methods. The input to a DA system can be a functional model describing the component, requirements of products, geometric models or variables, or others. Output from the system can be responses of analyses such as cost and performance, geometrical models, or manufacturing plans. The motivations for applying DA can be widely different. Where Cederfeldt and Elgh (2005), based on company interviews, state that the most used applications of DA are enabling of DO, automation of repetitive tasks (save development time/effort), generating design alternatives to support the ideation process and reducing the number of errors in the PDP. Rigger and Vosgien (2018) adds reuse of knowledge and existing solutions to the list of motivations.

As any other software system, DA systems must be continuously adapted to the changing needs from their operational environment to sustain their value (Poorkiany, 2015). That is, they shall possess a high level of maintainability, defined as the *"degree of effectiveness and efficiency with which a product or system can be modified"* (ISO/IEC/IEEE, 2022).

2.2. Design optimization

For the many decisions needed to be made in a PDP, design optimization can be a means of guidance and decision support by utilizing numerical optimization to find values of parameters of the product design with the objective of maximizing or minimizing a mathematical objective function, e.g., minimizing the material cost of a component. That way, design optimization can be seen as a way to replace iterations of processes within the PDP (Martins and Ning, 2021). Since most design problems contain a set of conflicting objectives, human decision making needs to take place to judge the relative

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importance of the objectives (Sobieszczanski-Sobieski et al., 2015) together with other factors such as aesthetics (which are more challenging to model and include numerically as an optimization objective).
In DO, design problems are formulated as mathematical functions where the goals of the PDP are formulated as objectives, the restrictions as constraints, and the parameters possible to change are used as design variables (Sobieszczanski-Sobieski et al., 2015). The characteristics of a component need to be formulated into mathematical expressions or outputs of simulations which can be automatically executed. Optimization problems can be single or multi-objective, convex or non-convex, and contain both continuous and discrete variables (Papalambros and Wilde, 2000).

2.3. Product customization

Being able to offer customization of products in an efficient way is the core concept of mass customization, where the aim is to be able to increase the ability of customization without a corresponding increase of costs and delivery times (Tseng et al., 1996). In a market with high customer demands, mass customization has become an essential means of staying competitive (Salvador et al., 2009). Achieving mass customization requires customer's being highly integrated in the process, as well as having flexible processes and production lines (Piller, 2004). For this, product configuration systems (PCS) are central enablers for mass customization (Hvam et al., 2008). PCSs has been shown to give positive returns on investment (Kristjansdottir et al., 2018), even considering their maintenance activities (Rasmussen et al., 2018).
On the production side, additive manufacturing (AM) is a way to increase the customization level (Wiberg et al., 2019). DA and DO are both enablers for generating feasible customization alternatives for customers as well as adapting production setups for each new customization case without extensive engineering for each order (Poot et al., 2020). A crucial task in mass customization enabled by DA and DO is being able to generate accurate quotations fast (Forza and Salvador, 2008; Wehlin, 2021).

3. Description and mapping of industrial cases

In this work, five industrial cases are analyzed and compared, to identify commonalities and limitations in today's DA implementations. The cases are gathered from previous research projects, and except for the commonality of being retrieved from industrial companies working with mechanical engineering products, the cases have been chosen based on a contrasting methodology, as described by Yin (2003). The systems have (at least to some extent) been developed in collaboration with industrial partners which also can be seen as receivers of the systems. Evaluation of the systems have been performed on design cases taken from the partners. The five cases differ in the motivation of applying DA, the phases of the PDP in which the solutions are applied, and which technical implementations are used. In general, case studies are used to describe how and why events and behavior appear and are therefore suitable to identify how organizational and technical factors affect a development process (Yin, 2003).
Section 3.1 introduces the cases by the presentation of in which context the industrial cases are performed, and which products are used. In section 3.2, details from the cases are compared.

3.1. Industrial cases

This section introduces five industrial cases where DA systems have been developed. Pictures showing the products in the five cases are presented in Figure 1.

3.1.1. Airplane bracket

Airplanes consist of numerous brackets and other similar components which build up their structure. In the aeronautic industry, each added gram equals added fuel consumption, increasing cost and environmental pollution. The fact that many components appear similar opens a possibility to use DA and DO to increase efficiency in the PDP and create lighter designs. In the developed DA system, a user can configure and optimize airplane brackets by selecting attachments areas and how trusses

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connect them. Based on initial placement and setup of a component the DA system updates the geometry, evaluated structural integrity, manufacturability, and manufacturing cost. Output is design with a trade-off between cost and being lightweight, as well as manufacturing instructions for selected designs. This DA system is further described by Wiberg et al. (2021).

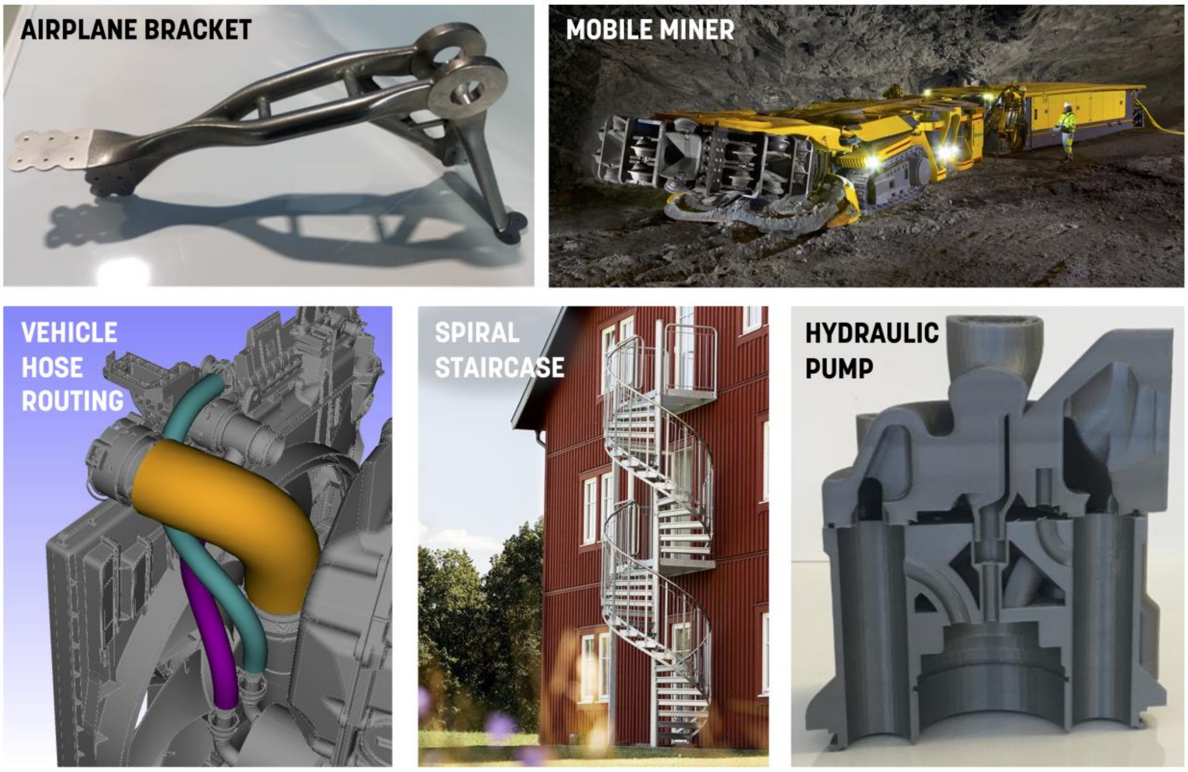

Figure 1. The five industrial cases

3.1.2. Mobile miner

The mobile miner case concerns the quotation and concept development phases for self-contained, mechanical rock excavation machines, referred to as mobile miners (Lyly et al., 2018). The machines are characterized by high complexity and financial risk, as well as full customization for each customer application, meaning that they can be considered as engineer-to-order products (as defined by Wortmann, 1983). To aid these processes and provide fast decision-support, an optimization framework has been developed, incorporating computational models controlled by a genetic optimization algorithm (Vidner et al., 2021a). Based on user input in the form of design requirements, the optimization framework searches for the design providing the best performance in terms of expected excavation rate, operational costs and technical constraints. This product data can be used to estimate the return-on-investment for the machine and the DA solution thus supports both engineering and sales aspects of the PDP.

3.1.3. Vehicle hose routing

Routing of hoses belonging to different subsystems in the engine compartment of a vehicle is a complex process. The hoses are subject to requirements of enduring vibrations, avoiding sharp edges and hot surfaces, as well as being cost-efficient and high performing for their respective subsystem. A DA and optimization system has been developed for the conceptual design stages of this process, with the purpose of generating feasible and optimized assemblies with multiple hoses. The DA optimizes the hoses individually but also consider in which order the hoses should be optimized and required via-points which the hoses need to pass through, thereby achieving a global optimization. This DA and optimization system is further described by Wehlin et al. (2020).

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3.1.4. Spiral staircase

Configuring the customized design of a spiral staircase contains elements of complexity connected to both design challenges in adjustments of parameters to fulfill varying legislations and standards as well as being comfortable to walk in, and challenges associated with information handling and translation in the process from sales to delivery and thus prone to errors. The spiral staircase design process contains both combinatorial tasks for designing new components. Subject for mass customization, a PCS containing a set of configurators built on optimization and design automation techniques has been developed for the stages from sales to detailed design. The system can both scan through an existing stock of components and evaluate the manufacturing of new ones during a company-wide optimization process. The PCS is further presented by Wehlin et al. (2021) and Vidner et al. (2021b).

3.1.5. Hydraulic pump

AM can manufacture complex channels and other structures that can be used to reduce pressure losses and improve the functionality of hydraulic pumps. In this case, a DA system that supports the design and analysis of hydraulic pumps produced by AM is developed. The DA system includes a configurator for schematic design of a pump, CAD automation that realizes the product model, and simulation models for functional and manufacturing evaluation. The configurator allows the user to vary product variables and get direct feedback on how the changes affect function and manufacturing. Finally, the framework supports manufacturing by automatic export of manufacturing instructions. This DA system is further described by Wiberg et al. (2022).

3.2. Case comparison

The DA systems developed in the five industrial cases aim to support different parts of the PDP and are all supported by DO, considering multiple engineering disciplines. Figure 2 illustrates which parts of the PDP the DA systems are aimed to support or be used in.

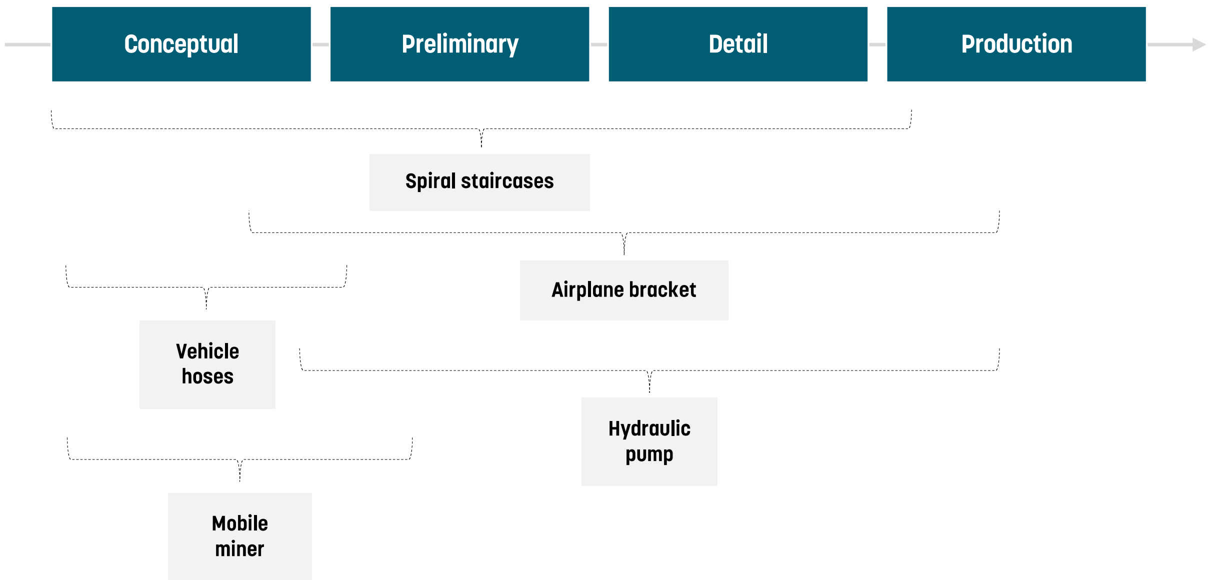

Figure 2. Description of which parts of the PDP the DA systems for the cases support

As described in section 2, DA systems cover a broad range of methods, and the motivation for utilizing them is often unique in each specific case. The five industrial cases in this work are no exceptions, but each system involves a spectrum of methods, and the aim also differs.
Figure 3 further displays the diversity of the industrial cases in the type of product or component that is included in each application case. It also displays that for some of the cases, the DA system is aimed at generating or supporting the process of making an equally *good* product, while in other cases, the

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aim is to generate or support the process of making a *better* product. *Good* and *better* in this comparison refers to for example, the product's or component's performance or durability. Figure 3 also outlines the models that are integrated in the developed DA systems for each of the cases.

	Aim of the DA system	Integrated models
Spiral staircases	Configure equally good products and more accurate quotations, with increased efficiency	• Cost • Production • Usability • Performance
Mobile miner	Configure better products and more accurate quotations, and thereby profit, by increasing knowledge of evaluated product configurations	• Performance • Structural integrity • Consumable consumption • Return-on-investment
Hydraulic pump	Create better products more efficiently by increasing knowledge of evaluated product concepts	• Cost • Production • Structure • Flow
Airplane bracket	Create better components that are cheaper to manufacture, by simultaneously design the component and manufacturing process	• Cost • Production • Structure
Vehicle hoses	Create equally good components with less iterations between departments	• Geometrical feasibility • Material cost • Structure

Figure 3. Comparison of the five industrial cases

4. Reflections from development of design automation systems

Considering the reflections of developing the design automation systems within the five industrial cases presented above, a number of issues can be identified. To gain a deeper understanding of these issues, they are classified along two dimensions: one dimension for the system's lifecycle, moving from *development* to *deployment*; and one dimension for the corresponding issue's character, moving from a *technical* to an *organizational* domain. Although the dimensions could actually be considered to work in a continuum, the classification is here simplified by dividing each dimension in two halves, resulting in a four-field matrix into which issues can be classified.

In the first dimension, development refers to the development of the systems themselves, for example product modelling and optimization problem setup, whereas deployment refers to the system being tested and launched in the intended (here industrial) context. The deployment phase of the project involves some kind of handover where a developed system needs to be transferred from the development setting to the users at the industrial partner which acts as receivers. The deployment dimension brings up the aspects of technical character, such as software-related issues, and on the other end the organizational aspects concerning for example knowledge acquisition or adjustments of processes.

The reflections from the case studies are presented in the following subsections and summarized in figure 4.

4.1. Technical-development

All the studied cases utilize simulation models to calculate product characteristics. Model integration in the cases is realized in different ways. In some cases (mobile miner and spiral staircase), the framework OpenMDAO is used to connect models. The commercial software ModeFrontier is used to connect models in the airplane bracket case while in-house solutions for connecting models are

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developed in the hydraulic pump and vehicle hoses cases. All these solutions have their own benefits and drawbacks. The main benefit of using a commercial software is the usability of the tool, but an important drawback in the academic setting is lack of transparency. OpenMDAO is an open-source solution but can be challenging to implement for inexperienced users. One challenge raised in the implementation of both solutions is a lack of flexibility in the possibility to change which models should be run and in which order for different product customizations. A customized in-house solution can be used to overcome this problem but is more time-consuming to develop.

To a large extent, the development time is dependent on the possibility to test and reiterate a system. An issue in this process is that models need to be run, and optimizations need to be performed to test the system before usage. In this process, simulation capability and time can make it very time-consuming to test a system.

A recurrent issue in the development of the DA systems is the upstart phase where new projects in many cases require a new set of tools and software. When developing systems in a research environment the selection of software often needs to be adapted to the industrial partner resulting in a phase of unknowns and problems for the developer.

4.2. Technical-deployment

A large challenge in the process of deploying a developed DA system, found in all the studied cases, is how the solution should be packed and shared with industrial partners and other receivers. The receivers are often not as experienced in software development and sharing a non-packed system that needs to be run from the terminal or development environment is often not an alternative if the goal is that the receiver should evaluate the developed solution. In this process it can also be a problem if the system involves commercial software with licenses unavailable to the receiver. Even if the receiver has the same software a problem can be if models or similar are developed with academic licenses not possible to run on commercial versions.

In most of the included cases the developed solutions are on a research level, meaning it is possible to be used by the research and prove that a method works. However, in some of the cases the maturity of the solution makes it difficult for an external partner to understand how to use it and not encounter to many bugs. From both an industrial and academic perspective, making sure that the different stakeholders can be involved early in the development process would probably contribute to a more clear and common view of the development goals.

Since developers (researchers) of the system in many cases have limited knowledge of the product or component(s), the system will likely need to be calibrated and adjusted both in a test-stage of the system and in a potential long-term use of the system (as the products will change/develop over time) in the intended environment where this product knowledge exists. Thus, both organizational and technical deployment challenges arise. The receivers of the system need to be informed and introduced to the system and aware of consequences related to changing system parameters. At the same time the system needs to be robust and flexible enough to make these adjustments possible.

4.3. Organizational-development

Among the organizational-development oriented issues and challenges is transferring of knowledge especially, in the early stages of the development process, as the design paradox depicts. This issue has been identified in all five cases. This is partly due to communication issues, which also is the factor of the other two identified issues and challenges within this dimension, namely the clear determination of the project scope, in particular the identification of the minimum viable product of the DA system which was identified in the case of the airplane bracket and in the hydraulic pump case. Establishing and following up the goals and progress of the project has also been limited in all five cases.

4.4. Organizational-deployment

A major challenge on the organizational side of deploying DA systems lies in integrating the systems into the current processes, which has been identified as an issue in the spiral staircase and vehicle hose

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routing cases. This is even harder when the receiver (or target process) is not clearly defined, due to key stakeholders changing roles or contact persons not having direct contact with the users of the system, a challenge apparent in the hydraulic pump case. Furthermore, the point raised as a technical deployment issue, regarding the limited knowledge on the constituent technical components also applies to the organizational side of deployment. Securing the knowledge transfer between academic and industrial parties is crucial for successful deployments of DA systems. To be able to use a system over time it is also often necessary with maintenance and update of the system. If the receiver at the company, then do not have full insight and knowledge of the developed system it fast gets unusable if the researcher is no longer involved in the system's lifecycle (for instance due to project closure or funding issues).

	Development	Deployment
Technical	• Establishing development environments • Integrating models • Managing software complexity	• Packaging the developed system • Software incompatibilities • Maintainability of system
Organizational	• Establishing and following up project goals • Identifying minimum viable product • Managing the design paradox	• Fitting system into current process • Unclear receiver • Receivers' technological knowledge of the solution

Figure 4. Summary of the identified issues within the industrial cases, mapped onto the organizational-technical and development-deployment dimensions

5. Conclusion

Developing DA systems has the potential of burdening the development team with *double* design paradoxes – the DA system is supposed to aid the PDP of a certain product, but the design paradox says that we cannot fully know how to develop the product until it has been developed. Likewise, the development of the DA system is a process in itself, governed by the design paradox: we cannot fully know how to develop the DA system until it has been developed. This magnifies the risk coupled with DA-supported product development processes and highlights the necessity of making the DA systems flexible enough to allow changes in their applications. It is therefore crucial that DA development is to be conducted with a high level of maintainability in mind, so that the DA system can be rapidly adjusted to the changing needs of its operational environment.

In the five industrial cases reviewed in this paper, DA has different roles. Both *design* and *automation* are broad terms, which is why the term *design automation* can be used to represent a wide range of different ideas. In the context of engineering design and the PDP, the role of DA could range from automating very specific tasks (such as the automation of a CAD modelling task) to more broad interpretations, as automation of the design process in a broader sense. These latter scenarios are where DO can be seen as a DA tool, for instance by being applied to automate tasks within the generation, evaluation and refinement of concepts. This can also be related to the motivation of introducing DA, as shown in this paper, DA can both be focused on improving the PDP or at improving the product. In the context of developing and deploying DA tools, the distinction between

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those interpretations could be necessary in terms of overcoming some of the organizational challenges by determining the role of the tool in the PDP.

The DA and DO tools of today incur both technological and organizational issues that limit their applicability in industrial settings. To tackle these issues, further studies are needed, looking into the requirements on tomorrow's tools. An important area for improvement on the technical side includes new ways in which model integration can be conducted to allow for more flexible formulations that can handle product reconfiguration automatically. This kind of flexibility could lead to a higher level of maintainability of DA systems (especially those supported by DO), ultimately leading to a more favorable return on the DA investment. On the organizational side, further investigations are needed, looking into the exchange of knowledge and into the change processes associated with the introduction of DA systems.

Overall, this work reflects on five cases where DA systems have been developed in a research environment together with industrial partners. The work highlights some challenges in the development of these kind of systems and proposes topics that should be further investigated to improve the process of developing DA systems.

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