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Exploring Conflicting Dynamics in Product and Production Development Within Industrialized House Building

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Abstract. The product realisation process is one of several formalized supports for industrial actors to excel in concurrent engineering procedures. To satisfy customers today mass customization is increasingly in need, requiring delicate modular architectures, both in product designs and production. Emerging is also the digitalized co-platforming era of automating the synchronization of product and production platforms. Yet, in all these processes, humans as agents have different roles, objectives, and mental models that governs their decision-making, being the bearer of separate ideas on what to optimize from their end. In product development large sensitivity is given to customer demands and trends to design attractive products, while less attention may be placed on evaluating the increase of variation into the production flows from new products, potentially increasing the workload and complexity of assembly systems, as well as, the subsequent material logistics. In production, much effort is invested to increase standardization, increase the pace, and minimize the manufacturing cost, with the objective to minimize required changes to the current production system. Consequently, it is a hard problem to satisfy all criteria at once, and how to solve it has no clear answer. Therefore, this study has applied qualitative System Dynamics modelling, also often referred to as systems thinking, to investigate how these opposing views were represented at an industrialized house builder. The purpose was to explore and model the perspectives and mental models of two leading roles to model their conflicting objectives. As a result, an overall model of main interactions of product and production development is proposed to support interpreting the findings, visualize the identified conflicting dynamics, and work as a vehicle for analysis.

Keywords. Product realisation, Production development, Platforms, Integration, Systems thinking

1. Introduction

The processes involved in realising products to the market in manufacturing companies with internal product development, including the systematization of product and production development activities and their intelligent integration, has increasingly become an essential capability [1]. Pressures from global trends such as increasing mass customization [2,3], shorter product life cycles [4], and recognition of sustainability [5] have occupied researchers to develop multiple approaches to support manufacturers to improve their performance toward this end, such as agile development methods [6], modularity in design and production [7], and platform strategies [8,9] to name a few. As

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well as, applying systems thinking and using dynamic modelling to learn during the product realization [10,11]. To endure on the market, these pressures have also induced endogenously generated changes for manufacturers, including systematizing their processes to realise products, developing more modular product architectures to increase commonality [7], and generally increasing the levels of resilience [12] in the production system to co-operate better with the increasing rates of exogenous market changes.

Within the field of industrialized house building, this evolvement of exogenous factors and endogenous responses have created increased pressures on improving integration management between sales and marketing, product development and planning of products, engineering and realizing specific designs, manufacturing and assembly in production flows including purchased sub-assemblies and components, and thereto the final assembly at the construction site [3]. While increased co-operation around introducing new products is beneficial and needed to support providing attractive products to the marketplace, manufacturing would still be supported by even higher levels of standardized modular designs to manage to implement increased modularity in production [7].

Prominent in value chains of organisations are working in silos which inhibits the overall process flow, and according to [13], the best lever for improving your sector often is due to someone else's part of the organisation and the benefits of changing at your end are reaped by someone else. Also, the power and influence are unevenly distributed, where the degree of influence often is higher upstream, such as the product development. Moreover, boundary management problems across organisational boundaries are inevitable. The ambidexterity of systems thinking is to embrace these boundaries and encourage thinking across them wherever possible [13].

Therefore, this study applies causal loop diagrams (CLD) from the System Dynamics (SD) methodology to study two silo functions that have a large impact on each other in the organisational value chain. The purpose is to explore the prominent conflicting dynamics persistent in the complex business of co-managing product and production development within industrialized house building. Where the proposed model visualizes the conflicting dynamics identified and is analyzed to generate insights. The findings can be generalized to any context which includes the conflicting objectives between mass customization and increased production performance.

The results, besides the interview syntheses, end up in exhibiting a CLD of the main condensed interactions between two contrasting perspectives representing the product and production domains to support orienting within the identified tradeoffs. Subsequently, two general strategies to improve from each perspective are included in the CLD and their dynamic consequences are elaborated on using the resulting model.

2. Frame of reference

2.1. Product and production platforms

The product realisation process (PRP) regards activities from product idea to efficient production through joint efforts of product development and production development [14]. Product realisation is often portrayed as a sequential process, yet, the realisation process is in dire need of cross-functional competencies and parallel processes, known as concurrent engineering (CE) to achieve shorter development lead times and less rework [1].

Mass customization enables companies to produce products with high customization at near mass production cost and has through industrialized house building been introduced to the construction industry [15]. Three fundamental capabilities have been identified to realise mass customization: (1) *solution space development* which aligns the variety of product attributes to the customer's requirements; (2) *robust process design* which structures the organizational and technical resources of the production and supply chain to fulfil the customer requirements; and (3) *choice navigation* which guides the customer in their solution to reduce decision complexity [16]. Product modularity is often seen as a cornerstone of mass customization to realise the conflicting objectives of high production efficiency and high product variety [17]. Mass customisation intends to facilitate the possibility to digitalise and automate the production of industrialized house building through increased standardisation of product and production [3].

Modularity has been defined, by [18], as building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole. Product modularization is a way to manage and reduce complexity in a product through thoughtful divisions and decompositions into sub-parts, often called modules [18]. This should enable the design of the product to be conducted through a series of modules that are integrated by pre-determined standard interfaces [19]. Modules are used to separate functions and means from each other to reduce the risk of unintended consequences while altering a function [18]. Utilising modularity enables companies to develop greater product and process variety to a limited increase in cost [18].

Within the production domain, modularity can be applied either by regarding the production system as a product [20] or by utilising the product's modularity and separate sub-assemblies from the main production flow to reduce complexity [18,21], by producing these either in a separate production flow or outsource them to a supplier. By adopting a platform strategy a long-term view can be applied to realise cost-efficient products based on utilising modularity and commonality between product variants and generations [8,9]. Product platforms cover two central questions in the long-term strategy, i.e., (1) what may change and what may not?, and (2) where is variety acceptable and where is it not? [22]. With the guidance of these questions, the product platform could act as a foundation from which derivate product variants can be created by sharing components and sub-assemblies [9].

The platform approach is commonly used in the product domain, but is relatively new within the production domain, lacking an established common definition, nor is a well-known concept within the industry [23]. Yet, three levels of abstractions could be used to distinguish different types of platforms in both product and production domain [24], where the *low level*, is composed of the physical embodiment of the product or manufacturing system. *Medium level* is the product and production system concepts and functions. And, the *high level*, as a collection of assets including process, knowledge, technology, and people and relationships.

2.2. System dynamics in product development

To apply SD feedback thinking is advocated for to investigate the dynamic complexity leading to growth and decline of capabilities and their effect on performance, e.g., [25,26]. SD is both a tool and philosphy to study complex adaptive systems derived from dynamic behaviour and interactions, where it provides a conceptual framework essential to the discovery of thinking about things [27]. SD has been considered appropriate as a structural theory for operations management [28], providing examples using CLDs as vehicles for reasoning on complex phenomena using mental simulation to understand why. And a set of system archetype models exists to support tinking, e.g., [13,29]. Yet, often computer simulation is argued the only tool to unveil the dynamics of SD models in full, see, e.g., the commentary in [30].

Problems are not merely physical, where the complexity arising around problems is not the issue, but the problem owners perceptions of them [31]. Thus, problem-solving capabilities become dependent on the agents' perceptions and understandings, also known as mental models [32,33]. In essence, mental models are inner simplifications people use to interpret the surrounding environment guiding people's actions. Hence, SD modelling aims to unveil the ambiguities of system problems to create a willingness to learn and challenge people's mental models, where the modelling process is as much a learning endeavour as is post analyzing the developed model [34].

Dynamic complexity in systems arise, according to [35], because: actors in a system are *tightly coupled* interacting with one another and with the environment all the time; these tight couplings make our actions *governed by feedback* where our decisions change the state of the world, causing others to act, a new situation arises, and influencing our next decisions; the path dependence of previous decisions determines possibilities of next action, creating *history-dependency*; also, the capabilities and decision rules of the agents are *adaptive* over time and people learn from experience; being embedded in these complex systems, it overwhelms our ability to understand them, resulting in *policy resistant* systems where many seemingly obvious solutions fail or worsen the problem; leading to *tradeoffs*, where the effect of inherent time delays in feedback often creates a long-run response different from its short-run response, and, high-leverage policies often cause worse-before-better behavior while poor policies temporarily induce an improvement before the problem grows worse.

Research using SD in product development has mainly extended the "Rework cycle" model from project management literature [1], e.g., [36–41]. These applications use a process-based model to simulate the work tasks and how different input conditions implicate to the simulated behaviour. Areas of evaluation includes, e.g., benefits from key attributes of Agile product development [37], the effects of CE [39], frontloading effects in lean product development from set-based design [42], and upfront investments using set-based CE [43]. Simulation runs calculate the total cost and lead time. In [44], they also applied an SD model to test the existing unanimous literature on team diversity attributes considered to impede, as well as, drive innovation in new product development teams, where simulation helped track the core of the issues to the contractionary explanations found in literature. Common in all these above SD cases is the useage of literature and reasoning to motivate specific input values, and to some extent changes to the applied process model to fit their cases, and then simulate to get results.

Studies using causal structures, such as CLD, to visualize empirical findings within product development, where the resulting model itself represents the explanation to observed phenomena from the stories of the interviewees, is less common. One such example was identified, in [45] they proposed a CLD to examine how manufacturers can balance formal and informal controls to improve collaborative coordination with suppliers in their PRP. To be successful, it centred around the critical asset of building up *Trust* to realize reducing investments in formal controls and that informal controls are not as profitable as expected.

All in all, these two types of applications serve different purposes, and the more commonly applied research within product development is using simulation models and fewer works focus exist on representing empirical findings using CLD.

3. Methodology

A single case study was conducted [46] within a large industrialized house builder where the product and production development process was studied. The company had both inhouse product and production development. They had several production units in Sweden where the final houses were industrially pre-fabricated in modules to different extents depending on the concept, before being transported on trucks to the specific construction sites for final assembly performed by contractors.

The study was seperated into two steps. First, an inventory of research needs to support long-term production development within the company was made. The inventory was based on an interview study including 11 interviews of diverse roles at the company, i.e., project managers, lead engineers, method and process developers, product platform engineers, CAD engineers, materials specialists, and production engineering. These interviews ranged between 63-107 minutes and were conducted by two researchers. All interviews were recorded and transcribed. The results were analysed, presented to, and verified with, the company in two workshops. Based on the results the researchers identified different themes to move forward. Based on the proposals the company replied interest in exploring strategies for thinking more long-term and achieving more of a common objective on orchestrating product and production strategies.

In a second step, which is the main focus of this paper, an opportunity to apply SD [33,35] was identified based on its potential merits to support exploring the possible conflicting requirements in integrating product and production development within the studied industrialized house building context. Therefore the planning of the study was designed to enable qualitative SD modelling using CLD, which uses the notation of causal links between variables explaining their interrelations connected into networks of feedback loops to explain phenomena [35]. To identify the variables and causal links to explain dynamic phenomena, qualitative data was collected through dedicated interviews to extract the mental models of two highly knowledgable subjects responsible for product portfolio management and assuring long-term factory productivity performance. The purpose was to study the co-operation between the product and production development by interviewing the two roles and extract their separate perspectives and to create one CLD of each. The interview guide was developed specifically to support constructing a CLD and also covered context-relevant questions, including, e.g., work procedures within and between units, including identification of strengths, good cooperations and challenges. Wether aspects have become better over time or have become worse were studied. The questions had the purpose to unveil time-dependent parameters and causal feedback relations and allow understanding of the conditions leading to the current state of business, and reasoning behind the intentions of expected future developments.

Hence, two semi-structured interviews were conducted and the same interview guide was used in both, and they lasted for 1.5 and 2 hours. The interviews were recorded and transcribed, and subsequently carefully processed, where a synthesis of each perspective, using thematic analysis [47], was carried out in iterations with attempts to create a meaningful CLD of each perspective. Each pre-synthesis was reviewed together with initial CLD models in a first meeting with the respective interviewee, lasting for 2 hours each to enable individual face validation [48]. After these interventions, further modelling was carried out, resulting in two main models that were presented in yet another 1.5 hour meeting including both interviewees to examine how the resulting models resonated with them, and to receive reflections on the presented models and perspectives. This occasion also allowed for verifying the relevance and usefulness [35] of the models' scope and objecting to errors in the interpretation of the empirical findings.

Subsequent to the above research process, the presented material herein has developed accordingly: 1) the aspect of destilling the two syntheses, due to the page limit a selection of most relevant information had to be made; 2) the specific CLD of the respective interview synthesis was large, due to the page limit these were post-processed, inspired by [30], to extract the main findings from the study. Hence, the proposed CLD was composed to exhibit the overall main interactions in one model to present the general conflicting and co-operating system dynamics identified from the empirical findings.

4. Syntheses of the interviews

4.1. The product domain perspective

The company strived to increase the control of new product introductions into the manufacturing and to streamline the product range, by introducing stricter control of new proposals. Previously, the main part of the product proposals was approved. Now, each proposal was carefully evaluated. By streamlining the product range a more coherent range could be reached from which variation to the customers could be designed. Consequently, a standard product range (SPR) could be developed over time where the subsequent need to develop the new blueprints in the product detail design phase could be reduced resulting in smoother assembly at the construction site.

Depending on the extent of a new product's deviation from previous products, and the current building system, based on modularity and product platform principles, the workload in the design phase was differently cumbersome and time-consuming. It also generated different levels of potential quality deficiency costs in the form of extra rework in the manufacturing or at the construction site due to unplanned stops.

By establishing the selection process of new product proposals, the implications of the desired changes could be analysed with the purpose to ensure that each product idea was tested against the knowledge about the capabilities of the building system and the production. Thus, an evaluation was conducted concerning whether the product proposal was comprised within the current capabilities and if so, the effort to perform it was also evaluated. The selection process was carried out through transdisciplinary dialogues with competencies such as the product platform, design, operations, and production engineering.

A result of the introduction of the selection process was that ideas also were rejected when not fulfilling the criteria. To avoid high numbers of rejected proposals, and to establish guidance in product idea creation, supports had been developed and their usage monitored. Hence, deviations can be learnt from and feedback into the dialogue with the developers to increase the understanding of these supports and improve them.

4.2. The production domain perspective

Within the production domain, the prominent goal was to increase the production throughput. To achieve this, automation was considered a pre-condition to attain the expected increase of production volumes. A pre-condition to enable automation was to refine the production flows to secure uniformity and positioning within the framework of certain product parameters. Products that did not follow this had to be treated outside the main production flow, e.g. be purchased as sub-assemblies. In this production modularisation process, it was also considered necessary to identify and gather existing core competencies, to identify the in-house production competencies and skills and to refine the flows in line with this.

In these processes, identifying and building the SPR by the product domain, was supported. Still, achieving the targeted high levels of pace was identified to require the efforts of many different people, with potentially different goals, understandings, and skills. An immense challenge to achieve consensus to prioritize the production pace requirement was considered to exist. Where, for example, those who worked with the SPR and the building system had to increasingly understand the production capabilities. Those who worked with the production system had to be able to better describe its limitations to facilitate the transdisciplinary dialogue. To achieve a higher commitment to these objectives, it was considered that higher management needed to identify appropriate product ranges and customer segments and communicate this better.

In addition to long-term needs, daily problems and improvements need to be handled regarding such as changes between product versions. The detailed consequences for the production of a new product concept were not always fully evaluated beforehand. The strived for increased production pace required long-term solutions to meet both long-term and short-term needs. Otherwise, the late product changes might have even more extensive consequences as deviations in the production flow occur.

Another potential aspect affecting the number of adjustments at the start of production was that several designers of the detailed drawings had limited insight into the production. On that note, training the sales and market division in how the building system works was another possibility to better match it with the production capability.

In future, it was expected that the number of considerations in need of being taken increase as a consequence of introducing higher levels of automation. Consequently, asking more from the early stages in terms of coordinated work and supports to that end. So, increased production capacity means lower flexibility around the introduction of new products and potentially longer development lead times that have not existed in the same way before. Hence, a future priority was to be able to decide early whether a new product project can be included in current production capability or require new investments.

5. Analyzing the dynamics of product management and production development

To comprehend the overall perspectives from both the product and the production domain one model was created indicating their dependencies. The CLD model, depicted in Figure 1, merges the two syntheses and model building processes of the specific perspectives. Hence, the purpose of this combined model is to highlight on the most generic scale the main interactions and identify conflicting system dynamics between the perspectives. The model includes one reinforcing feedback loop (R-loop) and seven balancing loops (B-loops) that create the dynamic forces identified as important for the integration between the perspectives. The walkthrough of the model will start with the loops related to the product management, then production development, followed by reasoning on the model dynamics from two strategies from each manager. The names of the variables and feedback loops are mentioned in the text using *Italics.* The arrows in the model are causal links where "+" means causation in the same direction as the causing variable, e.g., a reduction in *Revenues* leads to a decreased *Profitability*, in Figure 1. And, "-" means causation in the opposite direction.

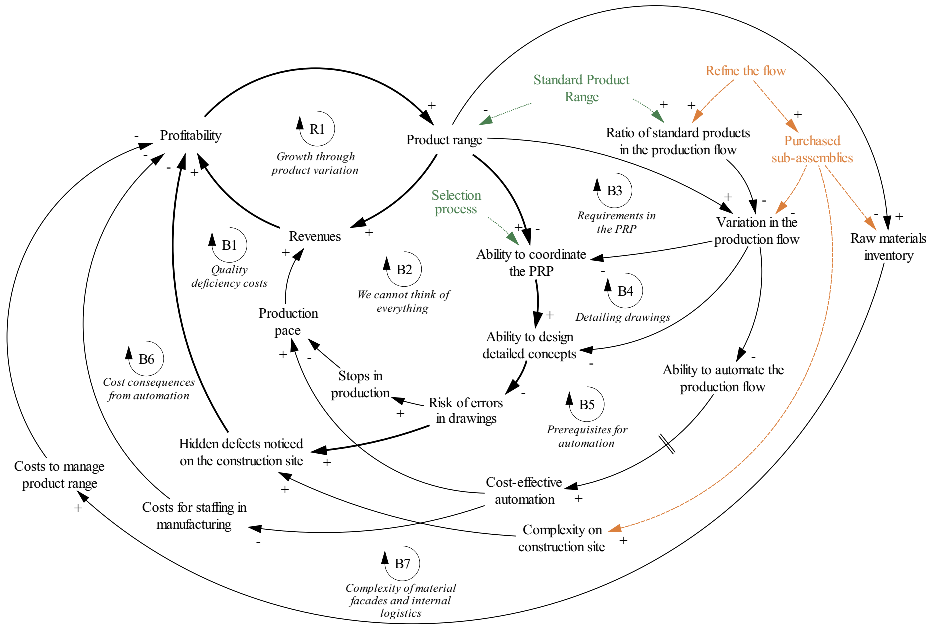

Figure1. The main interactions between the two perspectives of product management and production development, using Vensim software.

R1 - Growth through product variation: The R1-loop considers how the growth of the company is generated through attractiveness on the market by introducing a variety of products peoples want. Hence, resources are invested in efforts to introduce new products to increase the *Product range* to offer attractive house concepts to customers. This leads to more sold houses and increased *Revenues* which is the basis for generating *Profitability*, leading to the possibility to reinvest in further new development efforts creating the growth mechanism for making money.

B1 - Quality deficiency costs: A growing *Product range* shrinks the *Ability to coordinate the PRP,* which also reduces the *Ability to design detailed concepts*, having the consequence of increasing the *Risk of errors in drawings* unintentionally taking place due to lack of information and time to appropriately think it through. And with increased risk of errors, the higher probability of generating *Hidden defects noticed on the construction site*, thus reducing the *Profitability,* counteracting the growth mechanism in R1. The product domain perspective brought forward the issue of *Hidden defects noticed on the construction site*, which *quality deficiency costs* had grown to such proportions they negatively impacted *Profitability*, in need of being counteracted. Thus, more resources were invested to increase the coordination in the PRP to compensate for this, however, at the same time causing longer lead-time. The strategies of realizing a *Selection process* and a *Standard product range,* further treated below after going through the loops of the CLD, had formed based on the understanding of increased *quality deficiency costs.*

B2 - We cannot think of everything: A growing *Product range* leading to diminishing the abilities to coordinate and design detailed concepts increasing the *Risk of errors in drawings*, as in B1, was identified prominent to cause *Stops in production*, which with increased duration consequently decrease the *Production pace,* limiting the production volumes and consequently sales, and thus reducing *Revenues*. Without giving blame to any certain role due to there being many involved, it was stated that this happened rather frequent due to the current complexities with the explanation "*We cannot think of everything*". The CLD helps to indicate the connected dynamics leading to this situation, exposing the evident connection between reproduction of complexity from the growth in R1 and the duplication effects of B2 via increased *Stops in production* limiting the very intention to grow *Revenues*.

B3 - Requirements in the PRP: In close connection to B1 and B2 the B3-loop details how the *Product range* increases the *Variation in the production flow* in need of being contained. This increase further impairs the *Ability to coordinate the PRP,* and makes the process of mapping *Requirements in the PRP* more time-consuming. It exposes the derived connection between increased complexity and the ability to cooperate with it efficiently, eventually leading to reduce both *Revenues* and *Profitability*.

B4 - Detailing drawings: Similarly as for B3 the B4-loop exposes how the increased *Variation in the production flow* also directly leads to lessened *Ability to design detailed concepts* due to the increased considerations in need of being taken in the *Detailing drawings* process. It leads to an even higher probability of errors slipping through to production requiring immediate fixing as well as hidden defects on the construction site, further increasing the effects from B1 and B2 loops.

B5 - Prerequisites for automation: Additionally, the increase in *Variation in the production flow* diminishes the *Ability to automate the production flow,* leading to less *Cost-effective automation,* and no development towards higher *Production pace* as a consequence, not supporting building up more *Revenues* as intended; all due to the hardship of considering all relevant *Prerequisites for automation* from this increased complexity and variation.

B6 - Cost consequences from automation: Similarly as for the B5-loop this loop is also working through the ability to automate, leading to implementing less *Cost-effective automation.* In B6 it exposes an increase of the *Costs for staffing in manufacturing*, from automation still in need of manual staffing to compensate for not being able to contain the required variation of the products. Which reduce *Profitability*. The opposite is naturally sought for, meaning implementing less *Variation in the production flow* to make more *Cost-effective automation*, reducing the costs for staffing.

B7 - Complexity of material facades and internal logistics: An additional aspect from extending the *Product range* is the direct increase of *Raw materials inventory* to enable the supply of necessary materials to produce the products and the increased needs of material facades in the production flow and more components to manage in the internal logistics. However, these increased levels of material administration also create larger *Costs to manage product range*, leading to less *Profitability* on the total level.

All in all, the above-mentioned balancing feedback loops counteract the necessary reinforcing growth mechanism from generating attractive products. And, it becomes evident that the overall CLD exposes the need to somehow turn around the negative impacts from this prominent and necessary growth mechanism, to create *Revenues* and *Profitability* despite this fact, so the B-loops work in the opposite directions.

Two strategies from the perspective of the Product manager was prominent. One of them has its variable in green, *Standard Product Range*. And, the other strategy was to conduct a more systematized PRP, yet with the cost of a much longer lead-time to process new ideas and concepts from the architects and product developers. This strategy is implicit in the CLD but manifests around the variables *Ability to coordinate the PRP* and *Requirements in the PRP*. It is a well-intended strategy, which at this point has improved the quality output from these two processes, but it has also resulted in the mentioned drawback of longer lead-time. The strategy of implementing a *Standard Product Range* is applied through creating *external variation* towards the customers while at the same time reducing the *Product range* in need of being managed internally, thus reducing the *internal variation*. It causes improvements through the detailed feedback consequences of B1-B4 by turning around the causal chain effects, where a reduction of the *Product range* increases the abilities to work more systematically leading to fewer errors and finally supporting both increased *Revenues* and *Profitability*. This strategy also supports the perspective of the production development manager by an undirected increase of the *Ratio of standard products in the production flow* providing better conditions for reducing the *Variation in the production flow*.

Two strategies were also suggested by the manager of production development in orange, *Refine the flow* and *Purchased sub-assemblies.* Where these were pinpointed critical for creating the essential pre-conditions for automation solutions to attain the desired effects in terms of doubling the *Production pace*. The causal chains depicted by B5 and B6, highlight the importance of increasing the *Ability to automate the production flow*. Significantly, it raises the importance of the product management, that the streamlining of *Standard Product Range* should also consider the required need of the strategy *Refine the flow.* This was not known previously by the managers. These two strategies together purposefully create the reduction of *internal variation*, while keeping *external variation* towards customers, requiring even higher levels of modularisation of the product platforms currently existing in the *Product range*, in combination with the modularisation of the production flows.

6. Conclusions

This study has explored the conflicting objectives of mass customization combined with increased production performance at an industrialized house builder using a System Dynamics (SD) approach. The two domain perspectives of product development and production development were modelled using causal loop diagrams (CLD) and reported in meetings with the stakeholders. Herein, a combined perspective into one overall CLD is proposed prioritizing the main interactions identified. The causal relations between variables connects a set of relevant feedback behaviours where the conflicting tradeoffs within the two domains are exposed.

Each domain has its objectives that do not consider the objectives of the other domain. By connecting the two domain perspectives into one model it was clarified that even if the product management was highly systematic in streamlining the product range this was not connected to the objectives of the production development perspective. Consequently, the large potential exists in connecting the streamlining of the product range to the challenges of increasing the modularity and supporting standardized work in the production. Another insight is the increased level of clarity the CLD brings by mapping the different strategies, by facilitating the analysis of how the external variation can be increased simultaneously as the internal variation can be decreased.

In this paper, an overall CLD was presented in which the main dynamics were exhibited. It will be used in the continuing work with the company to further explore how the CLD models can support dialogue between actors in different silos of the system. It will also be applied in university educations on integrated product and production development to support studying and understand the difficult realisation of achieving the objectives in both domain perspectives at once. Where the model helps zooming out from individual myopic perspectives into more of a co-managing of product and production development. By allowing seeing a larger whole and nurturing more efficient strategies to coordinate activities it may lead to innovations towards a better performance overall.

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