# A Holistic Approach to Support Economic Motivation for Reconfigurability in Production System Development

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**Abstract.** The main contribution of this paper is to support how to economically motivate reconfigurability in production systems development. One main issue is the currently tendency to end up in dedicated production solutions unfit to future product features. By exploring the economic rationale for modularization concerning changeability in semi-automatic assembly systems using system dynamics simulation, we aim to advance sustainable practices in manufacturing industry. Currently, the traditional approach in product realization processes is to develop and industrialize one product at a time. However, this is becoming obsolete due to demands of more frequent product introductions, technological innovations, and sustainability requirements. Thereto, the trends of increasing variety and customization imply costly modifications during the production system lifecycle. To address the challenges, scholars advocate for using modular architectures in designing products and production systems, facilitated through product platforming. However, the economic rationale for product platforming encompassing production system lifecycle management is less reported. Using system dynamics simulation enables structuring several economic dependencies of reconfigurable modularization in the wider context of production system development, derived from empirical findings from four case studies. The results indicate considering long-term cost implications beyond the prevailing short-term economic frames is needed to nurture the industrial transformation towards sustainability.

**Keywords.** Modularization, changeability, reconfigurable manufacturing systems, economic rationale, sustainable manufacturing, system dynamics simulation

## 1. Introduction

The global landscape for the manufacturing industry is changing towards shorter product lifecycles [1], increasing product variety and mass customization [2], and at the same time decreasing the use of materials and energy in a circular economy [3]. These market trends entail significant costs related to modifications to production systems throughout their lifecycle and place substantial pressures on companies to sustainably optimize their product realization processes, and steps within it, to enhance their integration productivity [4] and delivery precision. In the digitalization era, various simulation approaches have emerged in support, such as simulation in product design [5], flow simulation in production development [6], and agile product development processes to reduce lead times and total costs [7]. Even so, many large companies struggle to implement more agile processes to be more progressive and forward-looking in their production development, often stuck in the mental model of considering one product at a time, confining the solution space to the here-and-now engineering issues to solve. Our experience is that this ignorance can easily be solved with enhanced awareness of adopting more of a reconfigurable mindset of the engineering staff. Yet, much of the structural conditions are defined by the organizational fragmentations and budget frames contradicting the implementation of a holistic approach across multiple projects separated by time and perhaps investment budget due to separated business areas.

Consequently, this paper addresses the need companies have to develop their internal capabilities to address these challenges to sustainably improve the integration productivity (the integration between the product developers and the production system developers) in their product realization processes. This can be accomplished by various methods, typically categorized as the development of co-platforming capabilities [8] or the implementation of reconfigurable manufacturing systems (RMS) [9] per se. With a theoretical foundation in these two realms, we recently proposed a production engineering support (see [10]) to evaluate modularization levels of semi-automatic assembly systems on a detail level, by decomposing and describing the production capabilities of each operation of the system to sustainably adapt to new product introductions. However, the pursuit of greater decoupling between product features and modular production system design solutions, as advocated by the approach, introduces several cost-related considerations. In this context of several ongoing projects with confined budgets, it becomes challenging to justify the economic burden on the current product project when an investment potentially leads to cost reductions only after subsequent product introductions are known and planned in detail, thus necessitating careful consideration of how financial resources are allocated across the stream of planned product introductions. To fully comprehend these financial consequences, in terms of potential costs and benefits, we advocate for a systems thinking approach. This implies expanding the problem boundary, to encompass a wider array of aspects included in the economic rationale of the financial consequences, and, enabling the formulation of hypotheses of the structural elements of the economic rationale and exploring possible system behaviours. The problem is that no such examples exist in literature and few examples exist that encompass parts of the descriptions of the above complex realities of various costs and benefits. For example, Boldt et al. [10] in their bottom-up approach, include estimated costs to expand each specific production capability to an enhanced level of modularity using the theory of RMS, where the cost-benefit evaluation is limited to a design space framed by project budgets. Helbig et al. [11], propose a method to encompass the lifecycle costs of decentralized component-based automation solutions and related costs. Neither of these proposes a strategic perspective to support industrial management in their decision-making, a gap addressed by our research proposal.

To encompass a sustainable perspective the system dynamics methodology [12] can offer a powerful logic to deal with issues in strategic management and support resource allocation [13]. System dynamics models define system elements and their interdependencies which allows to study of the rationale behind the emergent behaviours and importantly enables simulating their long-term economic consequences [14]. Therefore, based on combined empirical findings from four case studies, the inductive research approach of this study has the ambition to conceptualize to a more systemic degree than previous works the economic benefits of modularization.

Hence, one important purpose of this paper is to explore the economic rationale for modularization concerning changeability in semi-automatic assembly systems. Through the applied research approach, we aim to advance sustainable practices in the manufacturing industry and contribute to improved resource allocation in product realization processes with a focus on production system development. We examine two scenarios to contrast implementing either a dedicated or modular production system design. Where, adopting a dedicated mindset aligns with thinking case-by-case in product project management, and adopting a modular mindset implies using a cross-case project management approach, by assessing future unknowns proactively in the planning phases to a larger degree.

The paper is structured as follows: In the theoretical background, we review relevant literature on concepts like product platforming and reconfigurable manufacturing for sustainable production development. In the research approach and model building, we outline the collection of data and the research process behind the development of the economic rationale and model building. Thereafter, we describe the model focusing on its main aspects, and in the subsequent scenario analysis, we present two scenarios to study the effects of various volume uncertainties. Finally, in the discussion and conclusions, we end the paper and make some final notes to discuss model limitations, practical applications and future research.

## 2. Theoretical background

Within integrated product and production development, product platforms and concurrent engineering are the most prominent concepts [15] and serve to reduce lead time and cost in product realization and improve meeting the increased market demands. The synergy of the integration of product platforms and concurrent engineering is referred to as co-platforming [8]. Product platforming, as a concept, encompasses product platforms, production platforms, and other platforms existing in the entire value chain [16]. These approaches involve predefined platforms for both products [17], [18] and production systems [19], enabling flexible instantiation through reconfiguration or new development [20]. By sharing components and sub-systems, development time and time-to-market can be reduced, while minimizing disruptions to the production system.

Research has extensively explored product platforms, modular architectures, and manufacturing adaptability [21]. These studies emphasize efficient production and the reuse of manufacturing processes and equipment for different product variants. Similarly, within manufacturing, there is a focus on changeable paradigms and reconfigurable systems to address diverse product ranges and market dynamics [22]. Production platforms, including increasing levels of modularity, play a crucial role in co-platforming by promoting asset reuse and guiding change management [23].

Despite the theoretical groundwork, practical reports on using platforms in production system design and reconfiguration are limited [24]. The research often emphasizes conceptual aspects rather than practical implementation [8], [22]. In production system design, modularity supports more rapid adaptation, allowing systems to adjust capacities for changing product demands with minor adjustments, such as adding, removing, or upgrading modules [9]. Various models and methods have been developed for changeable and RMS [25]. These cover initiation, conceptual design, detailed design, implementation, and reconfiguration phases, but tend to focus on process structure rather than providing practical guidance. Moreover, with a few exceptions [10], [26], previous co-platforming literature primarily concentrates on greenfield development, neglecting the difficulties of implementing increased levels of modularization in the context of legacy work, and providing less guidance while considering existing production systems [23].

Consequently, the shift in manufacturing practices driven by the need for frequent product introductions, technological innovations, and sustainability requirements needs support to bridge the gap between theoretical frameworks and practical implementation. Bridging these gaps is crucial for companies undergoing transformative change towards a more sustainable economic rationale. While short-term investments may be required, the potential long-term benefits for manufacturing organizations in terms of resource allocation, downtime reduction, and enhanced production capacity are critical to include in formulating their economic rationale to support such strategic decision-making.

## 3. Research approach and model building

Our research approach is grounded in collaborating with four companies within the context of a multiple-case study, where our primary objective was to investigate how production systems could be better adapted to the challenges posed by shorter product lifecycles, increased product mixes, and uncertain production volumes. To address these objectives, we embarked on an interactive research approach [27] resulting in developing a support tool for mapping production capabilities, as detailed in [10]. A distinctive feature of this practical support tool was its capacity to compressively assess each production solution's capabilities. Specifically, it facilitated the identification of changeability levels based on the system's modularity, such as exchangeable grippers, adaptable fixtures, extra transfer lines, etc. It allowed us to assess the ease or difficulty of adapting a production solution to new product features. It equipped production engineers to prepare for eventualities such as uncertain volumes and unexpected new product introductions.

The multiple-case study was conducted in two phases, involving 2-3 representatives from each company, and included production engineering managers, production engineers, and project managers. Initially, we embarked on a 13-month journey with two of the companies to explore and create the above-mentioned support tool to map production capabilities. Subsequently, over 12 months we tested the tool's applicability, including the other two companies. In this process, we leveraged workshops [28] as a data collection technique to support an interactive research approach, totalling more than 54 hours of interactive engagement. The workshops were multifaceted, encompassing activities such as on-site factory visits, discussions regarding product requirements and the uncertainties associated with customer behaviours, thorough mapping of existing and conceptual production systems to craft the support tool, and coaching to facilitate progress.

Accordingly, beyond the development of the support tool, these workshops provided a platform for in-depth discussions. We explored topics ranging from cost implications of increasing modularity within specific production solutions to considerations related to the economic rationale for justifying investment costs, both within and outside project budgets. Consequently, in addition to gathering empirical data for the support tool, we gained invaluable insights into the challenges and consequences of transitioning from a single case-by-case project focus to a sustainable, cross-case project approach.

One of the most prominent challenges for the case companies was the difficulty of justifying increased investments, aiming to achieve modular and adaptive solutions within the constraints of a specific product project budget. Even if these could reduce costs in subsequent product projects. These types of considerations could only be bridged in "strategic projects" where the constraints of a specific product project budget could be considered lifted. It became evident that the shift in mindset required would need further materialization and understanding to create more fact-based hypotheses around potential effects using an increased time frame to support justifying increased investments. While the developed support tool's primary objective was to facilitate the integration of changeability in production development, enhancing production systems adaptability to future change requirements, the need to justify increased investments, to implement modularized production solutions over multiple projects, remained unaddressed.

To translate the principles underpinning the economic rationale and support the practical implementation, we addressed the issue with a systems thinking approach, resulting in creating a conceptual system dynamics model derived from a synthesis of the empirical data collected across the four cases. This modelling technique serves as a powerful tool for transforming these principles into equations that incorporate integrals and feedback loops, allowing for a transparent discussion of the assumptions related to identified input elements and their structural dependencies [14].

Applying more of a systems thinking perspective resulted in expanding the model's boundary into a cross-project context, encompassing the flow of product development projects through ten years in the same production system, rather than only considering a single product introduction in a case-by-case perspective. Importantly, we restricted the model's first iteration, presented herein, to a single semi-automatic assembly system and its evolutionary path. Consequently, the model examines effects stemming from production development projects as a consequence of product introductions. This implies that in this configuration, resource allocation conflicts within the product realization process are not included, and the model's output is dedicated exclusively to quantifying the impacts resulting from adopting either a dedicated or modular mindset in production development, with a focus on possible subsequent capacity constraints in operations [29] and calculated economic performance. Thus, at this stage, we do not consider dynamic dependencies that might emerge when considering a broader organizational perspective, such as prioritization of the engineering resources among portfolio projects [7].

In the studied cases, a distinct pattern emerged: adhering to the prevailing single case-by-case project focus was often associated with a dedicated mindset in production development. This mindset tended to yield dedicated production solutions, which, in turn, presented considerable challenges and costs when adapting to new product introductions later on. As a result, our proposed model presents two scenarios, which represent the implications of maintaining the case-by-case project focus with a dedicated mindset versus embracing the cross-case project approach and the shift towards employing modularized and changeable solutions when deemed suitable.

## 4. Model description

To describe the model, we split it into 7 aspects and explain the main reasoning that distinguishes between input for the dedicated and modular approach. Figure 1 presents where the 7 aspects are placed over the model layout to help navigate the detailed model in Figure 2. We recommend using figures 1 and 2 to follow the description.

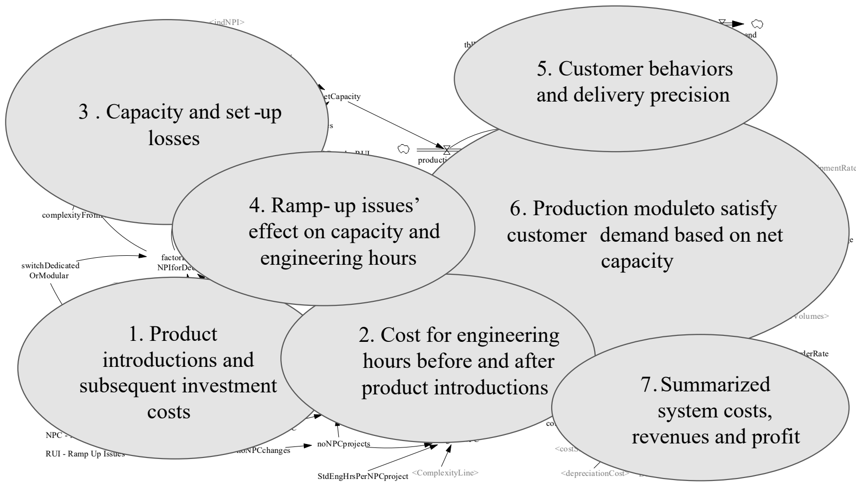


**Figure 1.** The seven aspects overlaid the model.

As a background, both scenarios have similar starting conditions, represented by a governing dedicated mindset, in the context of developing a semi-automatic assembly system. Based on the four cases, which all had elements of being semi-automatic but with various characteristics, we fused the findings of the data to design foremost the model structure of dependencies, as well as the applied average settings representing the dedicated and modular production system design respectively. This means specific numeric data is not of interest for the studied cases but to capture the core rationale (meaning the structure and dependencies) of the conceptual model. This approach serves to pinpoint the core similarities and differences between the two paradigms, subjected to the market conditions described in the introduction of shorter product lifecycles, increased product mixes, and uncertain production volumes. In these resulting market dynamics, the dedicated approach comes in short and a modular mindset may be more appropriate, however not visible until studying across a longer time. Moreover, this context is archetypical for the involved case companies even if they have various starting points and scales.

For the presented model the background conditions were the following. An assembly line was planned for one product and expected updates during its lifecycle. Shortly after, however, the expected customer volumes did not come, and another product had to be introduced to save the investment. Yet again, the second product did not meet the expected sales, and a third product had to be incorporated, and all three products, including their rather substantial differences, would need to be interchangeably produced. It could also be the case that we use the model in a prescriptive way, where we compete two conceptual production system solutions against each other. It does not matter. The problems emerging from applying a dedicated design are costly modifications because specific production solutions, with the lowest investment and solution space in mind, neglect flexibility to encompass more than one product variant. It is a consequence that a dedicated scenario follows the traditional sequential path of designing one specific production system solution per product introduction. The modular scenario instead, starts with engineers spending time to identify a production system design with modular and flexible solutions based on potential requirements and a thorough analysis of the industrial structures (transfers, pallet system, layout considerations, easiness of exchanging tools that are in interaction with the product through the line, see [10]). Several positive features from a modular approach for the resulting production system come as a consequence, but, to the cost of more engineering hours and equipment investments for the first evolution of the semi-automatic assembly system.

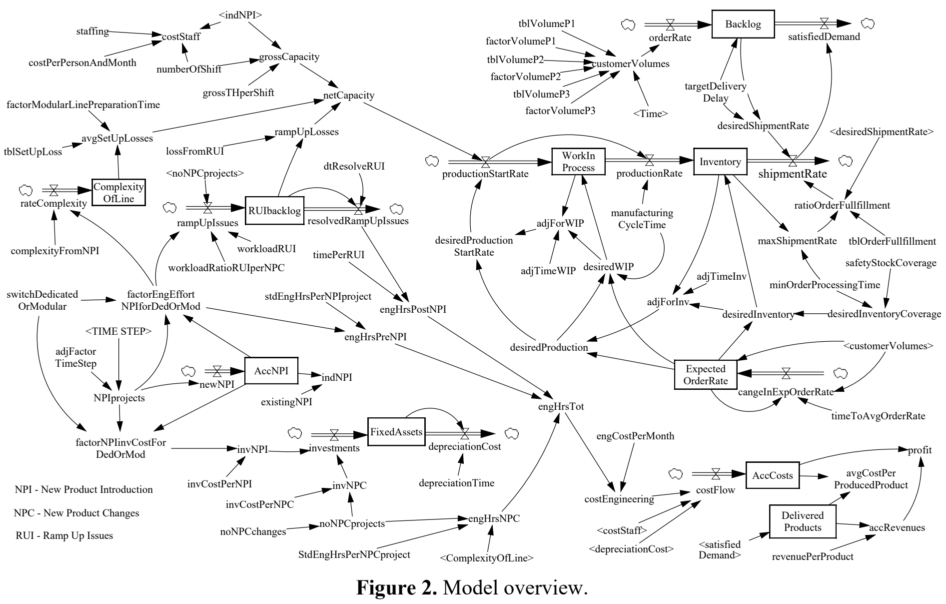

**Figure 2.** Model overview.

<u>*1. Product introductions and subsequent investment costs.*</u> New product introduction projects (NPIs) and new product changes (NPCs) are introduced within this aspect, generating their respective modification costs (treated as *investments* in the model). The frequency of NPIs is equal in both scenarios, the first at 6 months, the second at 30 months, and the third at 70 months accumulating in the stock *AccNPI*. Similarly, NPCs are introduced in both scenarios with a rate of 4 NPCs per year and product. However, investment costs for NPIs are considered differently. To calculate the investment costs for NPIs,

a factor is defined to separate the two. For the dedicated scenario, the factor is neutral (having value "1" for all three NPIs), meaning each investment to achieve an NPI is similar. For the modular scenario, the factor for the first investment is set to "1.5" (implying it is 50% larger than for the dedicated), and the second and the third are set to "0.5". This factor impacts the size of investment costs accumulated into the *FixedAssets* stock, from which the depreciation costs are calculated. Hence, the only difference between the two scenarios within this aspect is the estimated initial and subsequent investment costs as an effect of working following either a dedicated case-by-case mindset or an expanded mindset, incorporating modular and changeable technical solutions to prepare the industrial structures of the solutions to an increasing degree be adaptive to unknown product features.

*2. Cost for engineering hours before and after product introductions.* Within this aspect, the engineering hours as an implication of the amount of work required to realize either a dedicated or modular production system, before, during, and after the start of production, are summed up. To estimate the fundamental differences in preparing either a dedicated or modular production system considering the number of engineering hours needed (calculated in variable *engHrsPreNPI*), we introduced a factor (*factorEngEffortNPIforDedOrMod*) to represent the effort needed before completing the proposed production system design. This factor follows a similar reasoning as the one in aspect 1 above, where preparing the dedicated solution for the first NPI has a neutral factor (value "1"). For the second and third NPI, the factor defined requires twice the engineering hours due to major refitting needs to accommodate the new product features because previous solutions were dedicated to the first NPI. For the modular solution, an opposite pattern follows, where the work before the first NPI is set to the value "2", implying a double effort of engineering hours than is required for the dedicated scenario. This, is due to the required efforts to ensure well-thought solutions, while the efforts required for the second and third NPIs are set to half the neutral factor, having the value "0.5", due to the proactive thinking resulting in more flexible and adaptable production system solutions.

Following this reasoning, the effort factor is also used to measure the complexity of the line captured by the variable *ComplexityOfLine*, which simply accumulates the values of the effort factor over time. This implies for the dedicated solution that this index is lower for the first NPI, mainly due to that the line only has one purpose and the structural complexity of the line. Accordingly, for the second NPI the complexity index goes from "1" to "3", and for the third NPI to "5". The modular scenario starts with a higher complexity ("2") and for each NPI it adds less complexity per NPI due to being more adaptable. Accordingly, for the second NPI in modular scenario, the complexity index goes from "2" to "2.5", and for the third NPI to "3". The line complexity index is also used to estimate the engineering hours required for NPCs. This implies that the only difference between the dedicated and modular scenario in this aspect is the estimated effort factors, from which the resulting engineering hours before designing or redesigning a production system due to the NPIs (*engHrsPreNPI*) and NPCs (*engHrsNPC*) are calculated.

This is the case even for the remaining engineering hours included in the model generated after the solution is implemented, as a result of resolving ramp-up issues (RUIs), further described in aspect 4. From the various engineering hours (*engHrsTot*), see equation 1, the resulting total cost for engineering hours is generated (*costEngineering*), see equation 2.

$$engHrsTot = engHrsPreNPI + engHrsPostNPI + engHrsNPC \qquad \text{(Equation 1)}$$

$$costEngineering = engHrsTot * engCostPerMonth \qquad \text{(Equation 2)}$$

<u>*3. Capacity and set-up losses.*</u> Within this aspect, we quantify the gross cost of staffing and resulting net capacity after considering capacity losses. In our example, the gross capacity uses the same throughput for all NPIs, for simplicity and comparative reasons. This implies when only having one NPI, in both scenarios, the gross capacity equals the net capacity (in lack of changeovers between products). Hence, the net capacity is reduced by each introduced NPI as a consequence of introducing set-up losses (*avgSetUpLosses*) and temporal ramp-up issues (RUIs) resulting in ramp-up losses, described in the next aspect.

To define the set-up losses, we used a table function, see Figure 3, where an input value of “0” to “1” NPIs results in output “1” to reflect the reasoning above. And, since the effort factor for a modular scenario was “2”, we had to introduce a dimensionless factor (*factorModularLinePreparationTime*) with value “2” to have an initial value in both scenarios resulting in an output of “1”.

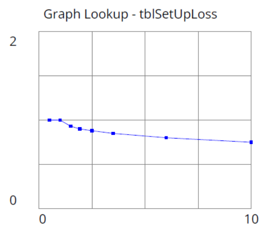


**Figure 3.** Lookup for set-up losses.

As seen by equation 3, for the first NPI it implies the maximum value is “1” using the max function. For higher levels than “2” in the input value of the complexity of the line will result in increasingly reduced capacity as a result of increased set-up losses in Figure 3. In our case was the resulting complexity of the line value for the dedicated scenario between “1” and “5”, and for the modular between “2” and “3”, according to the reasoning in aspect 2. This implies the dedicated paradigm suffers more from capacity losses than the modular, and in this way, we can quantify these implications to production, where reduced capacity will require more staffing costs.

$$avgSetUpLosses = tblSetUpLoss( MAX (ComplexityOfLine /$$

$factorModularLinePreparationTime, 1))$ (Equation 3)

*4. Ramp-up issues' effect on capacity and engineering hours.* Within this aspect the generated RUIs from following either a dedicated or modular approach are quantified. There are two sources of RUIs, those generated from NPIs and those from NPCs. The RUIs are considered strongly related to the variable *ComplexityOfLine*, thus, the effort factor is also used to generate RUIs from NPIs. This follows the previous pattern, where the workload generated by RUIs, represented by the inflow *rampUpIssues*, for the first NPI, is twice as large in the modular scenario compared to the dedicated, but one-fourth compared to the two subsequent NPIs. As is depicted by equation 4, the inflow of RUIs also includes the average workload from the NPCs which are similar across the two scenarios dependent on the number of NPIs currently in production, hence not considered in any further depths besides these RUIs are introduced on continual basis with an average value and not as events of workload as generated from the NPIs. The rate of the generated RUIs leads to a backlog (*RUIbacklog*), reduced by the rate of resolved RUIs (*resolvedRampUpIssues*), which generates the required engineering hours to fix the RUIs. This stock-and-flow structure for RUIs enables us to quantify the creation of RUIs and their resulting losses to gross capacity and required resources to resolve them. Here, the estimated values for the workload of RUIs caused by NPIs and NPCs also need to be set, the base values for these do not differ between the two scenarios. To make it as smooth as possible, we defined one RUI as generated from one NPI, and the variable *workloadRatioRUIperNPC* defines how many NPCs are equivalent to one NPI, where we set "50". Hence, it is only the effort factor that defines the differences between the scenarios.

$$rampUpIssues = factorEngEffortNPIforDedOrMod * workloadRUI + noNPCprojects / workloadRatioRUIperNPC \quad \text{(Equation 4)}$$

*5. Customer behaviours and delivery precision.* Within this aspect, the respective product volumes can be included, in our showcase, we introduce three NPIs and subsequent volume scenarios. This can be modified to fit the needs of a specific application. The idea of introducing volume scenarios is to enable manipulating their values to explore multiple volume scenarios and thereby discover various potential breakeven thresholds. The production module, described in the next aspect, is receiving its customer demand here. No difference in the model settings exists between the two scenarios within this aspect.

*6. Production module to satisfy customer demand based on net capacity.* This aspect includes a production module, directly adopted from a supply chain model by [12], that transforms the customer backlog into shipments. In our case, the constraint is the net capacity affecting the planning and manufacturing cycle time delays. Any simulation period of interest to evaluate delivery performance can be considered which allows analyzing how a dedicated or modular system may perform over product generations. Variables such as *Backlog* and *satisfiedDemand* enable studying the output performance.

*7. Summarized system costs, revenues and profit.* Within this final aspect, we accumulate all the cost flows, from engineering hours, staffing, and depreciations, to distinguish the performance of the two scenarios. As well as, accumulating the total amount of products delivered through time. This helps to calculate the evolving average cost per product and to observe the profit from various scenarios, as well as how they perform over time to study the cost and effects in both the short- and long-term.

*As a final note*, the review of the aspects describes the model's structural elements considered to enable more of a holistic inclusion of how the effects of applying either a dedicated or modular approach are impacting economic performance. It also becomes clear near all equations are generic for both approaches. Only two assumptions in the whole model distinguish the difference between the two approaches central to the resulting system behaviour and performance.

The first difference is introducing a factor that represents the estimated size of investment to introduce a product, the first time and the subsequent times during the simulated period. In our cases, one of the companies provided retrospective findings indicating the basis for the reasoning in the dedicated scenario, i.e., the subsequent NPIs to the first required as large a modification cost as the initial investment cost. Our assumption for how a modular production system design would deviate from this, based on reasoning with the company representatives, led to the arbitrary values for the first NPI being twice the size and the remaining ones to be halved. In any specific application, this assumption needs further scrutinization.

The second difference is introducing an effort factor, defining how NPIs affect various underlying conditions related to production systems development from both a process and industrial structure perspective, such as the size of engineering workloads and the complexity of the line resulting in different set-up losses. The arbitrary values for the effort factor set in our illustration are also subject to further scrutinization to delineate the delta values between the two approaches for a specific case, since, as was found in the studied cases, great variety can be traced to the legacy of the company (such as, way of thinking, organizational fragmentation, industrial structures, modularity in product design, production strategy, etc.).

All in all, the described economic rationale in the form of a system dynamics model can now be applied to study the ripple effects from either the dedicated or the modular approach in various volume conditions. To illustrate this, we present some scenario analyses to explore the economic performance.

## 5. Scenario analysis

In the scenario analysis, we investigate the characteristics of the dedicated and modular approach by using three new product introductions (NPIs) as explained in aspect 1 above. As the model description goes into detail with the economic rationale the scenario analysis will focus on some of the output parameters as an effect of the varying inputs which are the customer volumes.

In Figure 4, the customer volume for each of the three different NPIs is depicted, valid for the scenarios labelled “Mid”. We moreover let the first NPI be subjected to two more customer volume levels, one “Low” representing 50% of “Mid” and one “High” representing 150% of “Mid”. This is depicted in Figure 5, where the respective customer volume is added to each other in the variable *cutomerVolumes*.

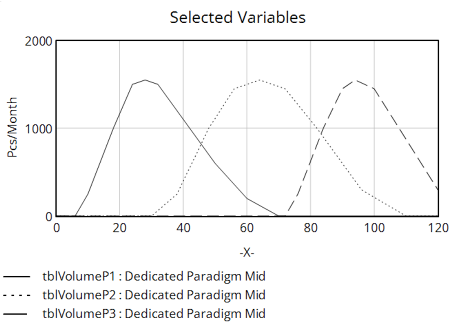


**Figure 4.** Customer volumes for the NPIs.

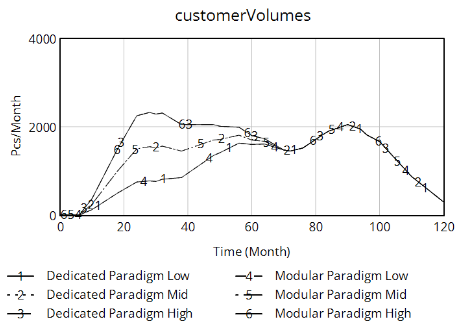


**Figure 5.** Added customer volumes and scenarios.

The high-volume scenarios for both dedicated and modular approaches are found to result in larger backlogs, see Figure 6. This can be traced to restricted shipments to satisfy the demands, depicted in Figure 7, see lines 3 and 6. This, in turn, is caused by restrictions in net capacity, as an effect of changeovers. At the second and third NPI, there is a basin pattern due to the ramp-up resolving RUIs as described in aspect 4.

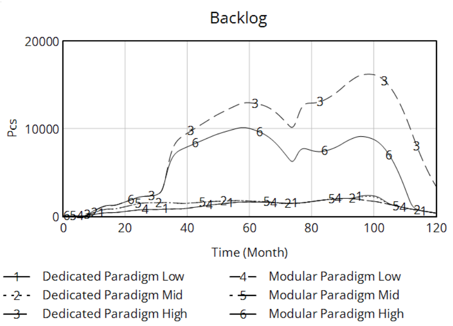


**Figure 6.** Customer backlog.

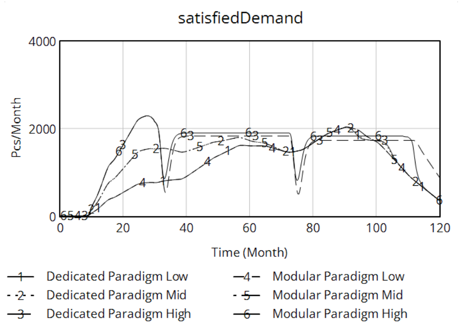


**Figure 7.** Satisfied demand/ shipment rate.

Studying the cost performance, Figure 8 depicts the summarized *costFlow* which does not depend on customer volumes (therefore only scenarios 2 and 5 are highlighted in the graph). It is seen that the modular approach has a higher initial cost for the first NPI while the dedicated approach has a higher cost for the two subsequent ones, as expected from the model description. We also see the operations costs in the dedicated approach for the first NPI are lower and for the third NPI are higher than for the modular, which is accumulated into the variable *AccCosts* to clearly illustrate the accumulation of all costs.

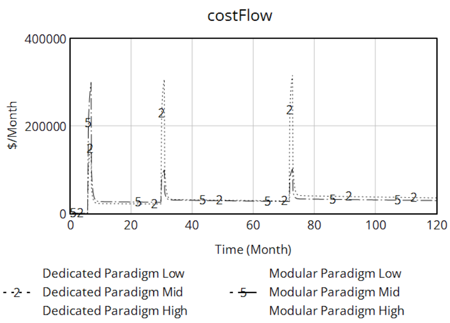


**Figure 8.** Generated cost flow.

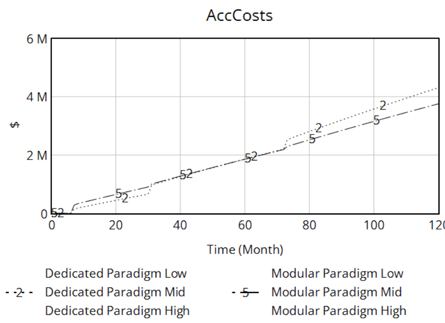


**Figure 9.** Accumulated costs.

The average cost per produced product is presented using Table 1, where we selected the smoothed average of each product. Hence, the value at month 30 only costs for the first NPI are included, at month 72 the costs for the first and second NPI, and at month 120 all costs are smoothed. In this comparison, we can see the tremendous impact the customer volumes have on the average product costs, as well as that the modular approach has the highest cost per product for one NPI, while for the second NPI the cost per product to par, to be lower until the end of the period of the third NPI.

**Table 1.** Average cost per produced product.

| **Time (Month)** | **30** | **72** | **120** |
|---|---|---|---|
| *avgCostPerProducedProduct* : Dedicated Paradigm Low | 64.4 | 34.4 | 32.1 |
| *avgCostPerProducedProduct* : Dedicated Paradigm Mid | 32.2 | 24.9 | 27.2 |
| *avgCostPerProducedProduct* : Dedicated Paradigm High | 21.6 | 21.2 | 23.9 |
| *avgCostPerProducedProduct* : Modular Paradigm Low | 88.1 | 34.2 | 28.0 |
| *avgCostPerProducedProduct* : Modular Paradigm Mid | 44.0 | 24.7 | 23.7 |
| *avgCostPerProducedProduct* : Modular Paradigm High | 29.5 | 20.3 | 20.5 |

Based on the *delivered products*, we can accumulate the revenues (*accRevenues*) and reduce them with the *AccCosts* to find the *profit* over time, as depicted in Figure 10. For both the dedicated and modular approaches with a "Low" customer volume scenario, we see breakeven is reached at about 60 months. For the "Mid" scenarios, we find the dedicated approach able to reach breakeven before the second NPI, which introduction introduces investment costs lowering the economic performance. For the "High" scenarios, we see the dedicated approach performs better for the first NPI compared to the modular approach, as well as best compared to all scenarios. However, during the second NPI, the profit diverged for the benefit of the modular approach already after the 40th month, and at the third NPI, the modular approach resulted in the best performance despite the successful start for the dedicated approach.

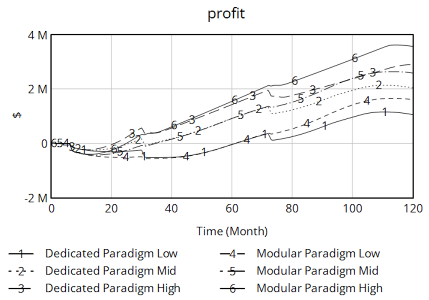


**Figure 10.** Profit.

Based on the scenario analysis we can conclude the differences between a dedicated and modular approach exist and can be explained, but may not be substantial. Hence, one main insight from exploring the economic performance of the two production system development approaches is that there is no “one answer” to how to economically motivate reconfigurability. “It depends”. What can be noted is that evaluating the value of modularization and changeability capabilities requires a longer time horizon to enable the potentially higher investment costs and benefits from thinking ahead to provide value. Our analysis is indicative, and naturally, large limitations are companioned with the illustrative case, such as the real revenues per product, cost for staff and engineering salaries, investment sizes, etc. These specifics will greatly impact a specific application case. However, there might be model structure improvements to consider as well, such as including regulation of the number of shifts to reduce any backlog or add costs for tied capital in inventories. Moreover, sensitivity analysis can be carried out to explore the combinations of uncertain customer volumes, as well as introduce more products. During the publication delays of this paper awaiting the conference proceedings, such a study has been carried out [30], and in it the Vensim model is found as supplementary material.

## 6. Discussion and conclusions

The main contribution of this paper is to provide results to support embarking on the difficulty of how to economically motivate reconfigurability in contemporary production systems development. In this paper, we present the results from having investigated the economic rationale for modularization and changeability in semi-automatic assembly systems. Based on data from the empirical findings we created a conceptual model of the identified rationale. The foundations of the modelling are based on the embodiment of product platforming theories, including reconfigurability and modularization, that in interactive research with engineers and project managers at industrial case companies generated insights to understand the holistic picture of all elements. Our inductive findings from four different cases use extracted empirical data to reason through the economic rationale to create the structure for a general illustrative system dynamics model. This is supported by depicting two main scenarios, with additional high and low customer volumes, to explore the implications of a dedicated production systems approach compared to a modular one.

The results indicate that to economically motivate reconfigurability investments with increased levels of modularization and changeability requires a longer time horizon than commonplace (meaning more than the pay-off time of a specific product). Moreover, the results are not only implying positive economic effects from increased levels of changeability, even if it is seen as beneficial from a theoretical perspective; indicating the multidimensionality of the problem under study. Therefore, the results indicate further investigations in more cases to explore additional trade-off dynamics in need of being implemented in the presented model structure. Further knowledge is required and in the process, the model can serve as a vehicle for representing the structural aspects of the economic rationale to inspire future research. As in any complex undertaking, it is the unique starting conditions and context that matter for how the trade-off dynamics will play out. In this light, it can be argued our model contains main aspects to help in the investigation towards assessing the economic rationale for motivating the value of modularization to a greater degree than contemporary approaches, perhaps mainly due to their non-existence.

In all, our research presents a holistic approach to motivate sustainable transitions using reconfigurability in production systems development based on the following: 1) inspire using a systematic approach to reason on the economic rationale of modularization and changeability in production development to bridge across potential organizational fragmentations created by economic frames in project budgets, 2) support the discussion that we are greatly assisted by system dynamics approaches to enhance sustainable decision-making in companies, and 3) support pedagogical development using system dynamics simulation in addressing complex phenomena within industrial management educations and research.

In conclusion, through our illustrative case, we hope to facilitate the unlocking of thinking more long-term in manufacturing organizations, where these insights may offer guidance for companies aiming for sustainable optimization of resource utilization, minimized downtime, and enhanced production capacity.

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## References


[1] Dombrowski U, Ebentreich D, Krenkel P. Impact Analyses of Lean Production Systems. Procedia CIRP. 2016;57:607–12. doi: 10.1016/j.procir.2016.11.105.

[2] Fogliatto FS, Da Silveira GJC, Borenstein D. The mass customization decade: An updated review of the literature. Int J Prod Econ. 2012 Jul;138(1):14–25. doi: 10.1016/J.IJPE.2012.03.002.

[3] Zikopoulos C. On the effect of upgradable products design on circular economy. Int J Prod Econ. 2022 Dec;254(108629). doi: 10.1016/J.IJPE.2022.108629.

[4] Vielhaber M, Stoffels P. Product development vs. Production development. Procedia CIRP. 2014;21:252–57. doi: 10.1016/j.procir.2014.03.141.

[5] Dogea R, Stolt R. Identifying Challenges Related to Industry 4.0 in Five Manufacturing Companies. Procedia Manuf. 2021;55:328–34. Doi: 10.1016/j.promfg.2021.10.046

[6] Goienetxea Uriarte A, Ng AHC, Urenda Moris M. Bringing together Lean and simulation: a comprehensive review. Int J Prod Res. 2020 Jan;58(1):87–117. doi: 10.1080/00207543.2019.1643512.

[7] Anderson EG, Lim SY, Joglekar N. Are more frequent releases always better? Dynamics of pivoting, scaling, and the minimum viable product. In: Proceedings of the Annual Hawaii International Conference on System Sciences; 2017. p. 5849–58. doi: 10.24251/hicss.2017.705.

[8] Landahl J, Jiao RJ, Madrid J, Söderberg R, Johannesson H. Dynamic platform modeling for concurrent product-production reconfiguration. Concurr Eng Res Appl. 2021;29(2):102-23. doi: 10.1177/1063293X20958938.

[9] ElMaraghy H. Changeable and Reconfigurable Manufacturing Systems. London: Springer, 2009.

[10] Boldt S, Rösiö C, Linnéusson G. Mapping Production Capabilities: Proposing Support Towards Changeable Production. In: Galizia FG. Bortolini M. editors. Production Processes and Product Evolution in the Age of Disruption. CARV 2023. Lecture Notes in Mechanical Engineering; Cham: Springer; 2023. doi: 10.1007/978-3-031-34821-1_36.

[11] Helbig T, Hoos J, Westkaämper E. A Method for Estimating and Evaluating Life Cycle Costs of Decentralized Component-based Automation Solutions. Procedia CIRP. 2014;17:332–37. doi: 10.1016/J.PROCIR.2014.01.117.

[12] Sterman JD. Business dynamics: Systems thinking and modeling for a complex world. Boston, MA: Irwin McGraw-Hill; 2000.

[13] Warren K. Improving strategic management with the fundamental principles of system dynamics. Syst Dyn Rev. 2005;21(4):329–50. doi: 10.1002/sdr.325.

[14] Linnéusson G, Ng AHC, Aslam T. Towards strategic development of maintenance and its effects on production performance by using system dynamics in the automotive industry. Int J Prod Econ. 2018;200:151–69. doi: 10.1016/j.ijpe.2018.03.024.

[15] Koufteros X, Lu G, Peters RC, Lai KH, Wong CWY, Cheng TCE. Product development practices, manufacturing practices, and performance: A mediational perspective. Int J Prod Econ. 2014;156:83–97. doi: 10.1016/j.ijpe.2014.05.017.

[16] Zhang LL. A literature review on multitype platforming and framework for future research. Int J Prod Econ. 2015;168:1–12. doi: 10.1016/j.ijpe.2015.06.004.

[17] Robertson D, Ulrich K. Planning for Product Platforms, Sloan Manage Rev. 1998;39(4):19-31.
[18] Meyer MH, Lehnerd AP. The power of product platforms : building value and cost leadership. New York: The Free Press, 1997.
[19] Sorensen DGH, ElMaraghy HA, Brunoe TD, Nielsen K. Classification coding of production systems for identification of platform candidates. CIRP J Manuf Sci Technol. 2020;28:144–56. doi: 10.1016/j.cirpj.2019.11.001.
[20] Michaelis MT, Johannesson H. From Dedicated to Platform-Based Co-Development of Products and Manufacturing Systems. In: 4th International Conference on Changeable, Agile, Reconfigurable and Virtual Production; 2011. p. 197–202. doi: 10.1007/978-3-642-23860-4_32.
[21] Boldt S, Linnéusson G, Rösiö C. Exploring the concept of production platforms – A literature review. Procedia CIRP. 2021;104(2):158–163. doi: 10.1016/j.procir.2021.11.027.
[22] ElMaraghy HA, Abbas M. Products-manufacturing systems Co-platforming. CIRP Ann Manuf Technol. 2015;64(1):407–410. doi: 10.1016/j.cirp.2015.04.110.
[23] Sorensen DGH, Bossen J, Bejlegaard M, Brunoe TD, Nielsen K. Production Platform Development Through the Four Loops of Concern. In: Hankammer S, Nielsen K, Piller F, Schuh G, Wang N, Eds. Customization 4.0. Cham: Springer; 2018. pp. 479–493. doi: 10.1007/978-3-319-77556-2_30.
[24] Brunoe TD, Andersen AL, Sorensen DGH, Nielsen K, Bejlegaard M. Integrated product-process modeling for platform-based co-development. Int J Prod Res. 2020;58(20):6185–201. doi: 10.1080/00207543.2019.1671628.
[25] Andersen AL, Brunoe TD, Nielsen K, Rösiö C. Towards a generic design method for reconfigurable manufacturing systems: Analysis and synthesis of current design methods and evaluation of supportive tools. J Manuf Syst. 2017;42:179–95. doi: 10.1016/J.JMSY.2016.11.006.
[26] Andersen AL, Rösiö C. Investigating the Transition towards Changeability through Platform-based Co-development of Products and Manufacturing Systems. Procedia Manuf. 2019;28:114–20. doi: 10.1016/j.promfg.2018.12.019.
[27] Ellström E. Knowledge Creation Through Interactive Research: A Learning Perspective, Linköping; 2007. Accessed: 2023-09-20. https://www.ltu.se/cms_fs/1.24923!/per-erik%20ellstr%C3%B6m.pdf
[28] Ørngreen EL, Levinsen RT. Workshops as a Research Methodology, The Electronic Journal of e-Learning. 2017;15(1):70–81.
[29] Slack N, Brandon-Jones A, Johnston R. Operations management, 8th ed. Halow: Pearson; 2016.
[30] Linnéusson G, Boldt S. Towards Assessing the Economic Sustainability of Reconfigurable Modularization in Semi-Automatic Assembly Systems: A System Dynamics Perspective. Systems. 2024;12(218). doi: org/10.3390/systems12060218