Exploring and *Adapt!* – Extending the *Adapt!* Method to Develop Reconfigurable Manufacturing Systems

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Abstract. Automotive production is faced with the challenge of bringing new products to market faster, with decreasing turn-around times, meaning production must be continually changing to accommodate new products. This paper proposes an approach to decrease a product's time-to-market, by increasing the efficiency of automotive assembly unit design. Providing designers with conceptual information about future vehicle models early in the product design process, could shift the design start forward and enable a more efficient transition process. Large automotive companies work on vehicle design and development for years before a product is ready for production. If during these earlier stages of product design, significant changes are identified and communicated to production designers, the manufacturing system design can get a jump start with an early exploration phase. A method exists, which uses the Axiomatic Design theory to develop Reconfigurable Manufacturing Systems through a modular breakdown. A similar method *Adapt!* employs Axiomatic Design and Scrum to develop changeable or adaptable production systems. This paper proposes to extend the *Adapt!* method to include an exploration phase, which through early communication, provides an overview of the required design process, and enables faster identification of the critical design challenges. A case study is performed by analysing a currently produced vehicle and its future electric version.

1 Introduction

The automotive industry is facing increases in product variation, competition, customization, and market volatility. The pace of technological advancements is also accelerating, further challenging the industry [1]. Figure 1, shows six different trends all having a huge impact on the automotive industry [2]. Being first to market and decreasing the time-to-market of a product provides significant benefits and profits [3]. Automotive manufacturing is therefore being pushed to accommodate the continual product changes faster and more efficiently. Through the implementation of engineering design methods, changeable and Reconfigurable Manufacturing Systems (RMS) can be strategically developed.

Reconfigurable systems change the physical or soft characteristics of a system to create a new configuration. According to Zhang et al. [4], RMS provide the highest level of adaptability for a manufacturing system. To enable practical reconfiguration, systems are broken down into modules.

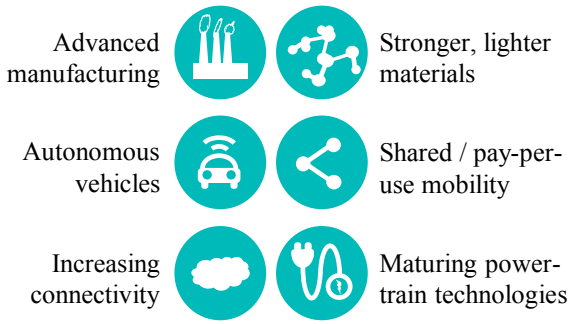

Fig. 1. Potentially disruptive trends [2].

Many methods have been proposed to facilitate modular manufacturing design. The Constituent Roadmap of Product Design proposed by Puik and Ceglarek [5] defines three chronological phases in project design: 1) exploration, 2) conceptualization, and 3) realization. For a truly holistic approach, all three phases should be considered. The exploration phase occurs before a particular project begins. This phase is relatively undefined in literature, however, many methods exist covering the phases of conceptualization and realization.

Puik et al. [6], propose a helpful method for implementing redesign for RMS once a product change has been initiated. This is founded on Axiomatic Design

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(AD) and offers clarity on project progression during design conception.

The method *Adapt!* has been proposed by Stäbler et al. [7] to capture the process of methodically designing and developing a changeable production unit based on. *Adapt!* combines a holistic evaluation process, with AD and the agile project management method Scrum to create a modern technology design process [8].

This paper proposes a novel expansion of the *Adapt!* method to include an exploration phase using an indexing method to bridge the gap. The aim is to provide a holistic approach to improve final assembly design and development through product-assembly pairing, communication, indexing and *Adapt!*. The proposed method is an amalgamation and extension of existing methods to cover the three phases of exploration, conceptualization and realization.

2 Previous Work

2.1 Product, Assembly, and Modularity, - in theory

Both the product, in this case a passenger car, and its assembly process have their own architecture. Two typical architectural structures are integral and modular [9, 10]. Integral architecture refers to a product or process whose subsystems have multiple functions, are dependent on one another, and whose direct interaction is not clearly defined. If one subsystem is changed, the entire product may be affected.

Modular architecture on the other hand, is defined by the product being separated into defined subsystems each with one or a few functional elements whose interfaces are defined. In a modular system, an element can be changed, while the rest of the subsystems maintain their functionality [9-11]. Modularity is not constrained to physical products. Processes, activities and components may also have a modular form [12]. Automotive assembly may therefore, also be modular.

Process modularity, refers to the different production processes being independent of each other. If individual production modules can be changed independently of each other, without impacting the assembly system, it can be considered a RMS.

RMSs are defined by Koren [13] as systems designed for changes in both software and hardware components to enable adjustments in production. It is therefore technologically essential that these systems are composed of a modular architecture. RMS offer scalability, an adjustable machine structure, and customized flexibility. Much research exists on the topic of RMS and it is considered by many to be the future of manufacturing systems [14].

Alone a modular product or modular production are useful, however an ideal system would have a modular product and corresponding modular assembly. Figure 2 shows an ideal product and assembly set up where all product and process modules are independent [15]. In a completely modular system, when the product design changes, the design and development necessary to adopt the change into production is narrowed to the affected module. Once this change is set in place, the design and development of the new process commences. Everything is independent and the entire system does not need to be considered.

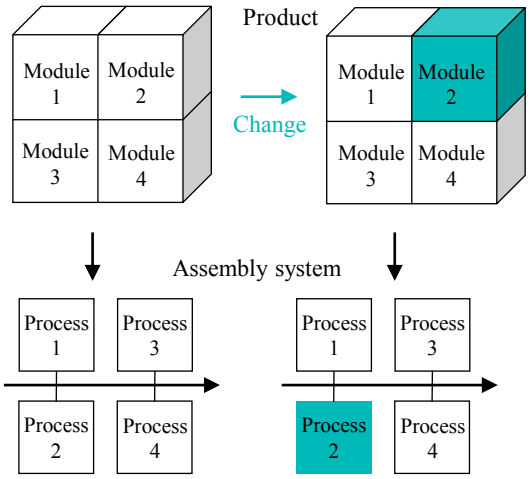

Fig. 2. Ideal modular product and assembly, after [15]

2.2 Product, Assembly, and Modularity, - in practice

In reality, nothing is ideal. As Ulrich [9] explains, nothing is one hundred percent modular or integral, but somewhere in between. The literature on passenger car architecture is mixed, some argue that the existing architecture is integral, however, others see it as modular. However, according to Ulrich, it is only a matter of the degree of modularity. Much research exists on dividing passenger cars into modules and different degrees of modularisation are found in industry [10, 12].

Most literature on process modularity for automotive manufacturing subdivides modules based on supplier-manufacturer relations. Most large automotive manufacturers have a wide array of suppliers providing smaller modules for the vehicles. An example would be a passenger seat; the seats are built from many smaller parts assembled together at a supplier's factory, the completed seat is brought to the large automotive plant where it is assembled in the vehicle. Some use the supplier parts as a way to identify modules, which are incorporated in the final assembly [4, 11, 16, 17]. This paper focuses only on assembly processes completed during assembly at the final vehicle-manufacturing plant. Modular assembly processes exist, however not on the scale of a full-vehicle [12, 15].

2.3 *Adapt!*

Adapt! is a design and development method tested and developed in the automotive industry in Germany [7, 8]. The approach enables a user-friendly design of changeable production units. The method combines a life-cycle with integrated change or re-design phases with AD.

2.3.1 Axiomatic Design

AD, a design theory proposed by Suh, provides a scientific basis for the design process using rational and logical processes. The design process uses four domains and two axioms to map out the requirements and solutions of a design [18, 19].

The four domains are customer, functional, physical and process. Customer requirements or attributes (CA) are gathered into the first domain, then converted into functional requirements (FR) in the functional domain. The mapping process commences through the answering of the questions "What do we want to achieve?" and "How do we achieve it?".

The second question leads to the design parameter (DP) in the physical domain. Through the repetition of these questions, the FRs are continually broken down until fully decomposed. The next step involves identifying process variables (PV) in the process domain.

The two axioms are the *Independence Axiom*, and *Information Axiom*. The *Independence Axiom*, as the name suggests, states that an optimal design guarantees the independence of all FR. The *Information Axiom*, focuses on reducing the information content of a design. In this context, the information context is related to the complexity of the proposed solution. [18, 19]

The *Adapt!* method uses a modification of AD and does not consider the second axiom. Further, *Adapt!* uses a color-coding system to link the FRs, DPs and CAs, with the department responsible for the requirement [20]. This colour coding helps clarify discussion and communication between the responsible departments, something often complicated in large companies with potentially complex organizational structures. Once the design task has been decomposed using AD, the development takes place using the framework scrum.

2.3.2 Scrum

Scrum is a framework for managing the development of complex products [21]. The framework outlines the project team, organisation, planning, communication, and breaks down the project time-line into fixed one month Sprints. Each sprint has specific goals and tasks to be carried out during the time period. The consistency and agility of the framework helps monitor progress and enables early response to unforeseen challenges. Scrum uses a product backlog, a list consisting of all product requirements which are divided throughout the sprints. *Adapt!* takes the results of AD as work tasks to fill the product backlog.

In summary, *Adapt!* uses AD to decompose the customer requirements into a detailed hierarchical tree of DP, and FR. These detailed elements are then used as tasks, allowing an agile Scrum team to continue the product development in a complex environment.

2.4 Indexing

When change is needed in a modular assembly process, the question arises, "Which modules need to be changed, and by how much?". Some modules may be able to remain the same, while others may need to be completely redesigned. Puik et al. [6] have proposed a method to index the modules based on axiomatic independence. Figure 3 shows the stages of the design progress. By indexing, or sorting, the modules into these phases, the design effort can be estimated.

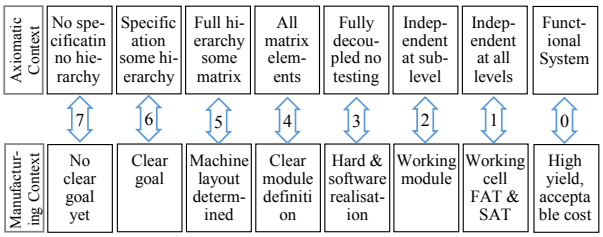

Fig. 3. Steps of RMS development [9]

In Figure 3 the phases are described in the context of AD and their mirrored position in a manufacturing context. By aligning these phases, the manufacturing development progression and AD progress can be easily understood and applied.

The seven stages have been recently simplified by Puik et al. [14], and consolidated into only three phases of reconfiguration. The three phases are described in Table 1.

Table 1. Simple classification of reconfiguration schemes [9].

Phase	Description
Repeat	Modules have been previously applied and documented, and the use case lies within a specified operating window. Module must only be tested to be at production level.
Adapt	Modules have been previously applied and documented, however the use case is outside the specified operating window. Module development is required to ensure the design.
Expand	Module does not exist und must be fully developed.

The simplification to three phases reduces the laborious effort needed to make accurate judgements for a large number of modules. This method ensures an effective assessment of the reconfiguration work needed. Having the design progress organised aids in planning, and enables an indication of the required resources and development ahead.

2.5 Design Process

Puik and Ceglarek propose three phases of the design process, exploration, conceptualisation and realisation. The exploration phase is where the project is defined. In this phase, the status of the project, parts and systems are unknown. The second phase, conceptualise, is where AD takes place. This phase poses to verify the concept and decouple the design matrices. At the end of this phase, the Independence Axiom is satisfied. The third and final

phase is realisation, or robustness. This phase is completed with a satisfied Information Axiom [5- 7].

The main contributions to this paper are the *Adapt!* method and indexing approach. The *Adapt!* method fulfills the final two phases of the design process. The conceptual phase is represented by AD, and Scrum represents the realisation phase. The indexing method is used in between the first two phases, to help clarify the remaining redesign process and clarify what is yet to be done.

This paper proposes to extend *Adapt!* to include an exploration phase at the front end of the design process, and uses the indexing process as the link tying the exploration and conceptual phases together.

3 Proposed Approach

This paper proposes a holistic approach to improve automotive final assembly design and development through product-assembly module pairing, indexing, and *Adapt* with a focus on product-assembly module interaction in automotive manufacturing. The entire method is shown in Figure 4.

Part 1. Modular Communication:

The method begins with part 1. Modular communication. This is in the exploration phase of the design process. The top two rows of the hierarchy tree breaking down into modules in Part 1 of the figure, represents the automobile product breakdown. The following two rows, similar but upside-down, are a breakdown of the final vehicle assembly line. The modules of the vehicle, and its assembly are paired together, for example, the windshield is paired with the windshield assembly unit.

In the product row, research and development (R&D) departments designing new vehicles identify changes between the model currently in production, and the future vehicle model in development. Production can rely on the R&D department to provide early information about incoming changes to the product. The turquoise highlighted modules represent "changed" modules. The corresponding assembly modules are also highlighted. These changes are communicated with the company's production unit designers. The relevant experts from both sides of the affected modules, product and assembly, can now discuss implementation of the changes.

The modular breakdown of both sides enables easy communication between product development and manufacturing assembly teams at a module-specific level. Once focused discussions have occurred between the responsible groups, constructive collaboration can be initiated, long before the final design is finished. This enables early indications of change to be communicated within assembly before any detailed new product information is available. During these early communications, production unit designers can start an exploration phase and get a head-start in preparing for the design process ahead.

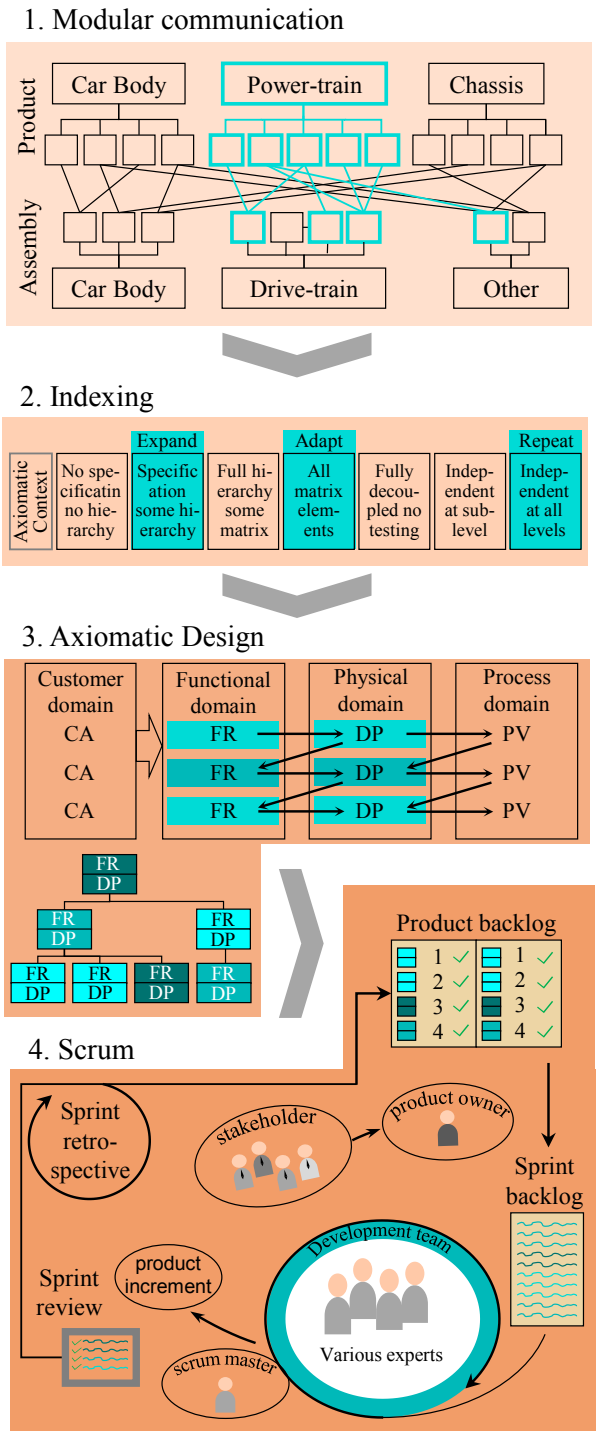

Fig. 4. Proposed holistic approach

Part 2. Indexing:

The second part of the method, is based on the indexing method proposed by Puik et al.. Once the affected modules have been identified, analysis is done to assess whether the current assembly process is suitable to produce the new model, or whether new assembly units must be designed. Experts rank the assembly modules based on the three phases (Repeat, Adapt, Expand) outlined in Table 1. If it is determined that some design is necessary, the production unit designer can orient the phase into the axiomatic context. The three phases are highlighted in axiomatic context in blue in Part 2 of Figure 4. When the indexing process is

complete, this information is used to evaluate the required design and development effort, and time-to-market for the new model. Now that the axiomatic context is outlined, the remaining AD can be completed.

Part 3. Axiomatic Design:

The *Adapt!* method is then implemented to complete the assembly unit design and development. The Independence Axiom of AD is used to further decompose the remainder of the design task. Again, a colour code is used to link the FRs and DPs based on the responsible department. This color coding is demonstrated using the different shades of turquoise in Figure 4. Once the Independence Axiom is satisfied and the final design matrix is complete, a design concept is ready to enter the development phase.

Part 4. Scrum:

At this point, the production unit development is a more dynamic and practical effort. In Part 4, the transition to the scrum framework begins. The designer is joined by a team consisting of experts in different fields. The scrum framework supports an agile and self-directed working group. In *Adapt!*, the transition from AD to scrum takes place using the product backlog. The design parameters are put into the product backlog and once fully defined, enter the sprint backlog. The scrum team uses these defined tasks to complete the development of the production unit.

4 Modularity and product-assembly pairing in Industry

To enable the application of the proposed method for current products and assembly in industry, an analysis of the existing modular situation is necessary. The appropriate pairing of modules is also needed. Once the product and assembly are organised into appropriate subsystems, verification of the method can be accomplished.

A verification case study examines the switch from production of a conventionally powered vehicle to the production of an electric model. This is an example of a maturing power-train technology, identified as a potential disruptor in Figure 1. This disrupting technology is applicable to all automobile makers. To transform the assembly line for the production of the electric models, several modules would be affected, enabling a platform to verify this method using a practical industry case.

To apply the proposed method, the final assembly must first be arranged in a modular fashion and paired with product models. However, in the automotive industry today, existing vehicle assembly methods are typically non-ideally-modular. Based on current industry information and evaluation of existing assembly plants, final assembly is separated based on assembly order, vehicle assembly area, and assembly lines.

A case study at Daimler AG found that the entire final assembly is not organized into modules, however, some modules exist within the current assembly structure. In Figure 5, the assembly modules currently being used today and their appropriately paired product modules are shown. The modules affected by the change from a conventional drive train to electric are highlighted in turquoise. The next step is to commence communication between the groups responsible for the now turquoise modules. Now, based on the existing modules, the indexing can be performed. Each module shown in Figure 5 must now be assessed for whether it is in design phase is in a state of Expand, Adapt, or Repeat. According to ranking, the by the remaining design and development is to be completed using axiomatic design and scrum.

An added complexity to the modular form is the assembly lines. Assembly lines use fixed conveyor belt technology, and are therefore limited in their flexibility and location. Each module in the assembly must center itself around the conveyor belt. If the conveyor technology is not modular, the entire assembly has limited modularity. Further, the modules presented in Figure 5 do not include the entire vehicle, all its parts, and assembly.

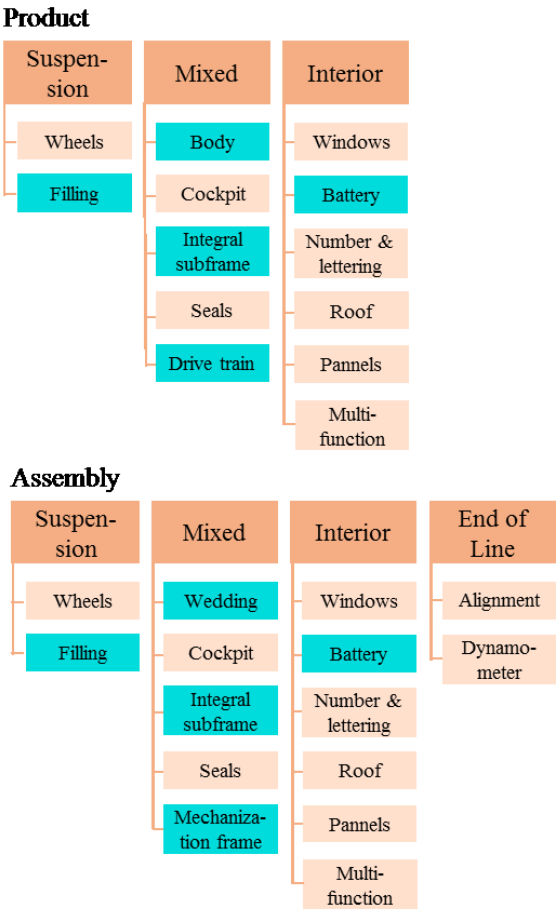

Fig. 5. Product and assembly modules

5 Discussion

During the pairing process, it is quickly evident that process in the end of line, typically testing procedures, are doubly paired with the product modules. The product module is connected to its assembly module as well as its testing and/or calibration process module. For the affected modules, all three parties are should to take part in the discussion.

Some concerns arise when considering the selected modules. A proper modular structure should limit dependencies, therefore the module interrelationships used here must be studied and multiple function integration should be evaluated. For an industry applicable method, it must be considered that existing modules do not necessarily have independent requirements. Following, during the continued design process using AD, further dependencies could arise which have not been originally considered. The method is lacking formality.

6 Conclusion

This paper proposed an extension of the *Adapt!* method, to improve automotive final assembly design and development. A modular architecture is used to enable early communication between product research and development, and production design and development. The modular architecture enables indexing and estimation of remaining design effort. Following which, design and development is carried out with the agile and user friendly *Adapt!* method. A case study for the modularisation of the assembly line is completed and the changing modules identified.

To further the validation of the application of this method in automotive assembly, future work is required in completing the modular decomposition of current assembly lines to attain independent modules. Once the remaining modules are identified, they can be paired with product modules. Additionally, an examination of the interdependencies of the current modules could increase the efficacy of the method. The case study on a realistic industry example, of the assembly transformation from conventional to electric vehicles, can then be completed.

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