EXPLOITING THE SUSTAINABILITY POTENTIAL OF MODULAR PRODUCTS BY INTEGRATING R-IMPERATIVES INTO PRODUCT LIFE PHASES

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ABSTRACT

Climate change and the growing consumption of natural resources has made it increasingly clear that engineering must focus on the development of more sustainable products. To do so, the methodologies for developing products need to address sustainability. However, many of the frequently used methodologies, such as Modular Function Deployment (MFD) or the Life Phases Modularisation (LPM), do not do that sufficiently. The product life phases, these methodologies are based, only address sustainability in the form of recycling. That is why a broader approach to sustainability, such as the R-imperatives, is not considered. Therefore, in this contribution, the model of product life phases is extended by integrating the R-imperatives. Furthermore, the module drivers resulting from the extended product life phases that are necessary to apply the MFD and the LPM are developed. Finally, the positive impact of the developed module drivers on the product architecture is shown by applying the resulting method onto an industrial example.

Keywords: Modularisation, Circular economy, Sustainability, Product architecture, Design for X (DfX)

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1 INTRODUCTION

The extent to which resources are consumed and how the resulting waste is dealt with has always been a concern for mankind. One reason is that it has become clear that resources like fossil fuels are finitely available (Kranert, 2017). In recent years, this circumstance has already led to unconventional methods of resource extraction being pursued in order to meet the demand for raw materials (Franke et al., 2022). Another reason is that increased consumption of resources is accompanied by an increased volume of waste. The disposal of which may be harmful to the environment and the disposal of which is increasingly costly with higher demands to quality (Kranert, 2017). For this reason, approaches have been developed in recent years for recycling products after their primary use has ended, in addition to scrapping them (Campbell-Johnston et al., 2020). The newly developed approaches affect all aspects of a product, from components and the materials they are made of to the product architecture. Examples for methods for product architecture design are the *Modular Function Deployment* (MFD) and in it the method of module drivers from Erixon (Erixon et al., 1996) or the further development of this approach as *Life Phases Modularisation* (LPM) (Simpson, 2014). The objective of this paper is to extend the product life phases used in the LPM to include other approaches to a circular economy. The different stages that a product can go through are summarized in the R-imperatives. These imperatives represent strategies for making a product more sustainable by, for example, reducing energy and resource consumption. Therefore, these imperatives are integrated into the existing model of product life phases. Subsequently, module drivers needed for the LPM are assigned to the R- imperatives. The module drivers are derived from a list of advantages of modular product architecture that are related to sustainability. Finally, the method adapted in this way is applied to an example of a product family of pressure reducing valves, on basis of which the more sustainable product architecture resulting from the introduction of new module drivers is demonstrated.

2 STATE OF THE ART

2.1 Product life phases

The term product life phases is often used synonymously with departments in companies and was initially defined by Erixon (Erixon et al., 1996; Krause and Gebhardt, 2023). From a product development perspective, the generic life phases are: *Sales, Development, Procurement, Production, Assembly, Usage, and Recycling* (Krause and Gebhardt, 2023). The sequence of these life phases is mainly influenced by the underlying corporate strategy. For example, in an Engineer-to-Order strategy, Sales is at the beginning, while in a Make-to-Order strategy, the first phases are Development and Procurement before the life phase Sales begins (Krause and Gebhardt, 2023). This is shown in Figure 1. In addition to the sequence of the generic life phases, their respective characteristics are also company-specific. If necessary, the generic life phases can also be split into pre-assembly and final assembly, for example, if these are performed separately in terms of time.

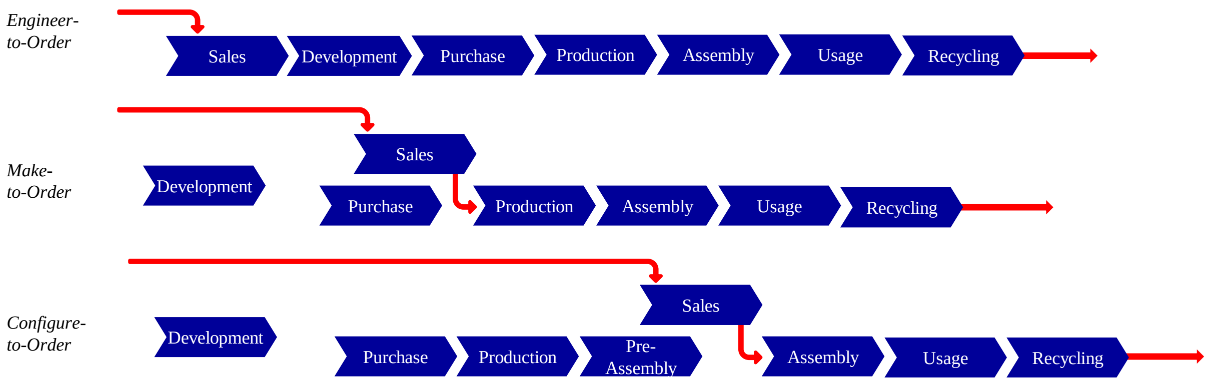

Figure 1. Examples of generic life phases and business strategies (Krause and Gebhardt, 2023)

A detailed analysis of the life phases is relevant for the development of modular product families, since in each life phase different advantages and disadvantages can occur due to modularisation

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(Krause and Gebhardt, 2023). The exploitation of the potential of a modular product in a life phase may lead to disadvantages in another life phase. For example, the reuse of modules shortens the development time (development life phase), however, at the same time, this can increase oversizing in the usage life phase, which has a disadvantageous impact on customer satisfaction. An overview of the advantages and disadvantages, as well as the underlying effects and causal relationships, is summarized in the *Impact Model of Modular Product Families*, see Schwede et al. (2022).

2.2 Modularisation methods

In literature, a variety of different methods and approaches exist for the development of modular product architectures. These can be divided into two groups: the technical-functional and the product-strategic approaches.

In technical-functional approaches, modules are defined based on functions or technological constraints. Examples of such methods or tools are the *Design Structure Matrix* (DSM) (Eppinger und Browning, 2012) or the heuristics according to Stone (Stone, 1997). However, methods from this group do not address the varying needs of different life phases. In contrast, life phases are taken into account by methods of product-strategic modularisation. *Modular Function Deployment* (MFD) (Erixon et al., 1996) is an important basis for the methods in this group, where module definition is based on module drivers. In simple terms, module drivers represent reasons for combining certain components into a module. The generic module drivers according to Erixon et al. are shown in Figure 2. The MFD approach was taken up by Blees et al. and developed further in the context of the Integrated PKT-Approach for the development of modular product families for so-called *Life Phases Modularisation* (LPM) (Krause et al., 2014; Blees et al., 2010).

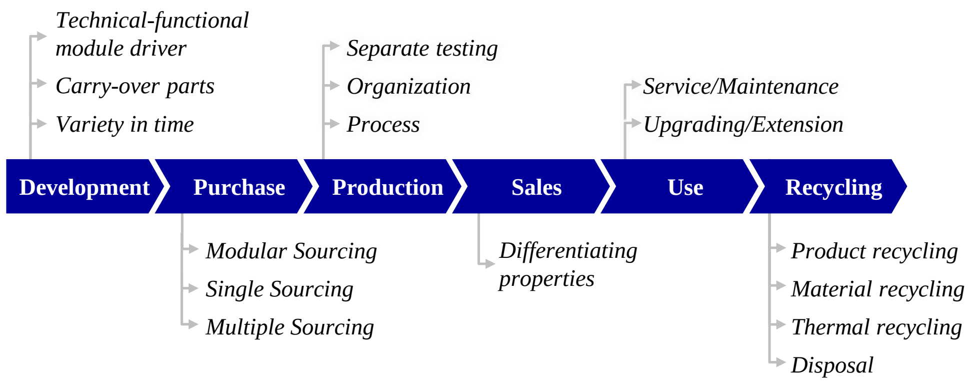

Figure 2. Generic module drivers according to Erixon (Erixon et al., 1996; Krause et al., 2014)

2.3 Detailed analysis of life phases

Within the framework of LPM, so-called network plans are created for each life phase. In these, the generic module drivers according to Erixon et al. are linked with the components. On this basis, the module structure for each life phase is created. To support the assignment of module drivers and components, an intermediate level known as module driver characteristics is introduced. The module driver characteristics specify the module drivers and thus adapt them to the respective company or product. The schematic structure of a network is shown in Figure 3. For example, in the case of a robot vacuum cleaner, the module driver *Separate testing* is assigned the module driver specifications *Suction test* and *Electrical test*.

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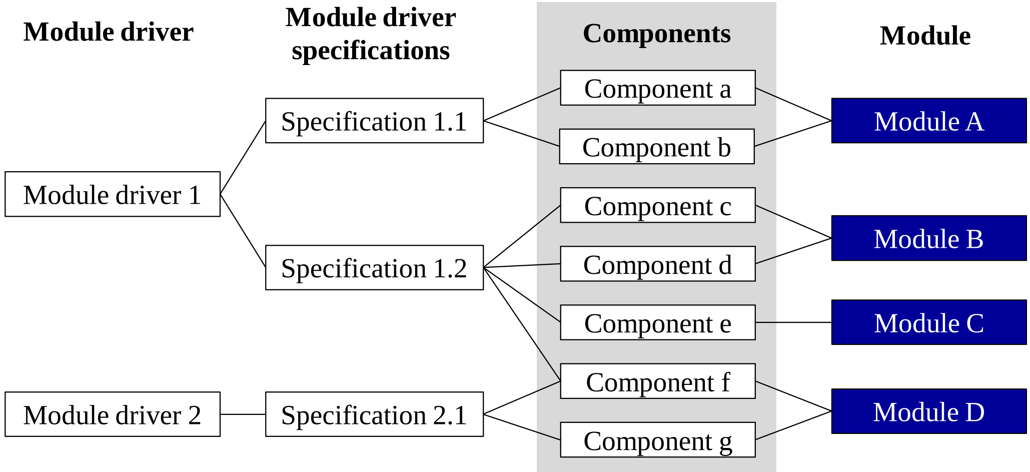

Figure 3. Example for a network plan

To align the needs of the different departments and to find a modular product architecture that represents the optimal compromise for all life phases, the network diagrams created are harmonised in a Module Process Chart (Krause et al., 2014; Blees et al., 2010). As shown in Figure 4, the module structures are presented in columns side by side, so that it is apparent where contradictions between module requests arise (Greve et al., 2020). This representation is used as a basis for finding compromises.

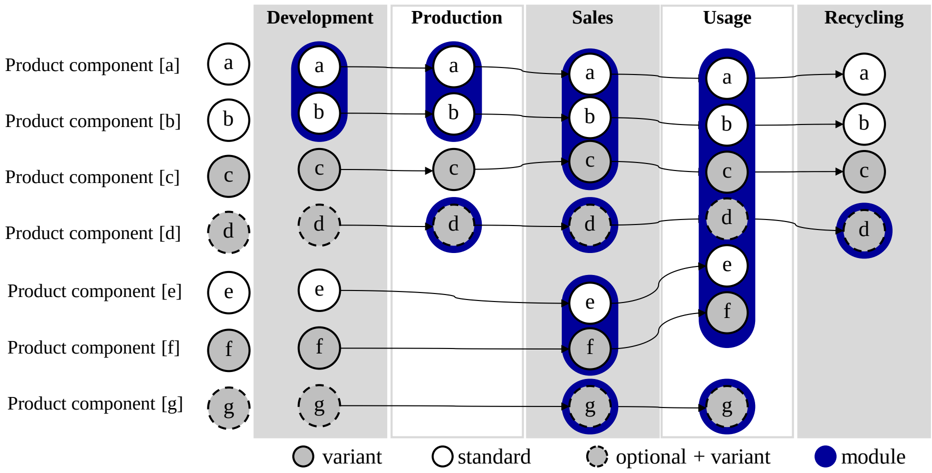

Figure 4. Example for a module process chart

Life phase modularization as a method has been applied and also further developed in various projects in recent years (Greve et al., 2020). An aspect that has been integrated into LPM is the consideration of services in order to modularize so-called *Product-Service Systems* (PSS) (Rennpferdt and Krause, 2021). Since physical products and services have different characteristics, they must also be handled differently in different life phases. In relation to the life phases, the focus shifts from low-cost manufacturing of products to low costs during usage when considering PSS. Since PSS are usually not sold, but rather billed according to use, the *usage* life phase becomes much more important and may need to be considered in more detail, as different "sub-life phases" may alternate within usage. As part of the further development of LPM for PSS, it was shown that the additional consideration of services also results in new module drivers (Zuefle et al., 2022).

2.4 Circular economy

Another aspect that is becoming increasingly relevant is the aspect of sustainability. This issue has already been addressed by e.g. Mörtl (2003) and Crone et al. (2000), who aim to achieve better sustainability properties of products by realizing upgradeability. Since the development of sustainable products often happens only in an evolutionary way, Diaz et al. (2021) suggest a stronger emphasis on

earlier tasks such as strategic product planning. This aspect so far has only been explicitly considered in life-cycle modularisation as the module driver *recycling*, see Section 2.2. Although recycling material at the end of a products life phases improves its sustainability, it does not fully exploit a products sustainability potential. A more general approach to increasing sustainability lies in the transformation from a linear to a *circular economy* (CE) (Kirchherr et al., 2017; Geissdoerfer et al., 2017; European Comission, 2020).
Although this approach is not new, there are still different definitions of CE in literature. While CE initially was mainly understood as the recycling of waste materials, this understanding has changed to one of maximizing the value retention of materials used in times of dwindling resources (Reike et al., 2018). Various approaches of value retention can be found in the literature, which Reike et al. summarise to ten R-strategies which are shown in Table 1 (Reike et al., 2018). The circularity resulting from the application of the R-imperatives is displayed in Figure 5.

Table 1. R-strategies summarised by Reike et al. (2018)

R-Strategy	Description
Refuse	Buy or use less in consumer case. Avoidance of hazardous materials and waste in producer case
Reduce	Lower use of materials und products
Reuse/ Resell	Use of a product by a second user
Repair	Extending the lifetime of a product by replacing defect components
Refurbish	Overall structure of a multi-component product remains intact while components are being replaced or repaired to bring the product up to a specified quality
Remanufacture	Full structure of a multi-component product is disassembled and checked, components get replaced or repaired if necessary
Repurpose	Using a product or parts of it for other functions
Recycle	Processing of mixed streams of post-consumer products or post-producer waste streams
Recover	Capturing energy embodied in waste, linking it to incineration in combination with producing energy
Remine	Retrieval of materials after the landfilling phase

Thus, while the focus was initially mainly on the end of the product life in the linear understanding of the life phases, it is now not only on the entire product life, but increasingly on product development, in which the product is defined to a significant extent (Bocken et al., 2016). Furthermore, modular product architectures or Product Service Systems can be enablers for circular economy (Diaz et al., 2021). So far, however, there have been few approaches to taking sustainability aspects into account in the early phases of product development.
Mesa et al. (2018) show linkages between circular economy and modular product families, more specifically their modular properties, and propose several indicators to assess circularity. However, the proposed indicators are independent of conventional measures of sustainability such as energy consumption or emissions, so further research is needed to enable a holistic consideration of sustainability (Mesa et al., 2018).

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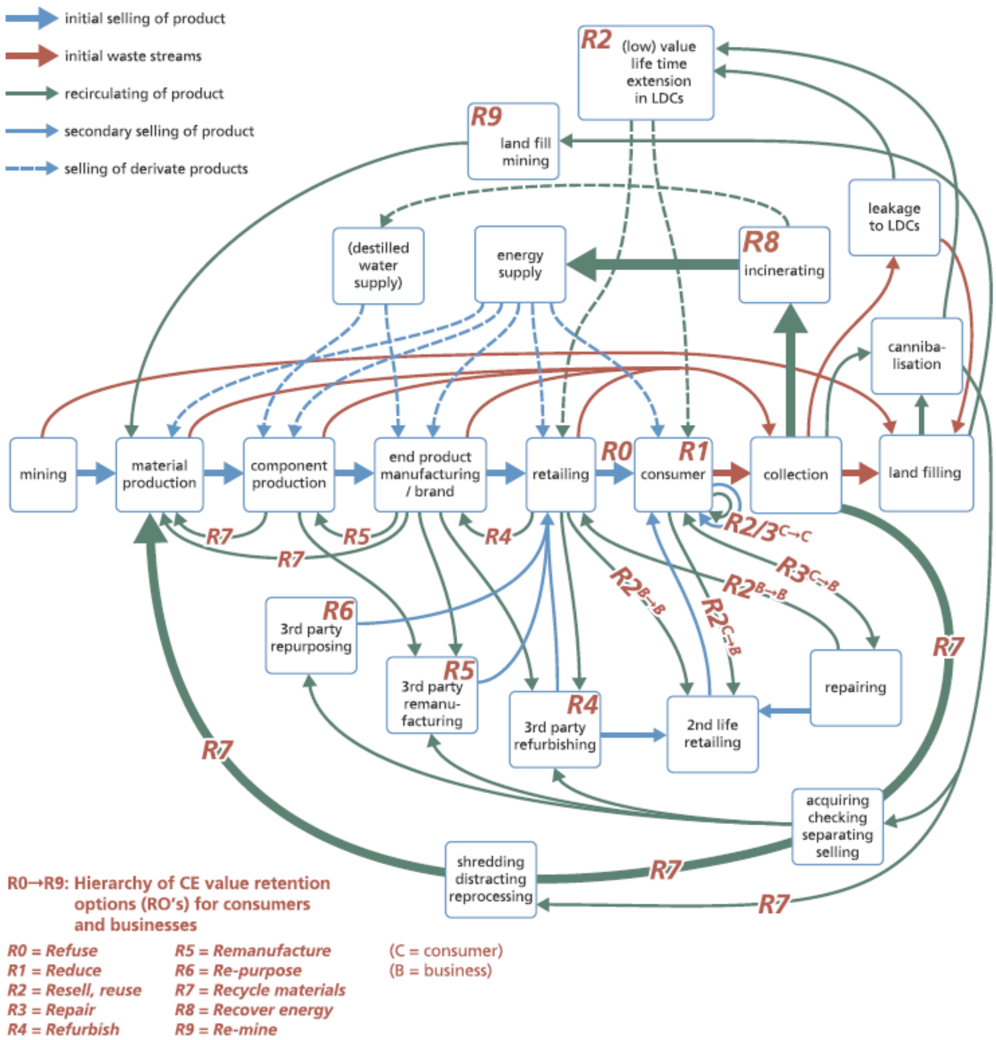

Figure 5. Mapping Circular Economy Retention Options: The Product Produce and Use Life Cycle (Reike et al., 2018)

3 INTEGRATION OF R-IMPERATIVES INTO THE PRODUCT LIFE PHASES

In order to integrate aspects of sustainability into the MFD or LPM, the R-imperatives and the product life phases need to be combined. The models, that the R-imperatives are embedded in, are focusing on the stakeholders such as manufacturing, production and retailing. However, the product life phases consider the stages that a product is going through, not considering the stakeholders involved. Therefore, it is not possible to simply use the existing models since the MFD or LPM would not be applicable and the existing module drivers would no longer be considered. Therefore, the R-imperatives need to be integrated into the existing product life phases. The resulting model with the influence of the R-imperatives (light blue) is displayed in Figure 6. The grey connections between the product life phases mark the communication between the stakeholders responsible for the individual product life phases. These connections are necessary for a successful product development. The resulting connections of product life phases via R-imperatives only display a fraction of the connections mentioned in Section 2.4. This is again due to the fact, that the LPM is focused on the stages a product goes through rather than the involved stakeholders. This can be illustrated by the fact that in Figure 1 the life phase is called *Usage*, whereas Figure 5 is considering the consumer. Therefore, integrating all possible ways an R-imperative can be integrated into the product life phases leads to redundancy. That is because the same module drivers can be developed for every individual R-imperative regardless of the stakeholders involved. Furthermore, some of the R-imperatives are not regarded as suitable for the development of module drivers. This regards the R-imperatives *Reduce* and *Refuse*, since the development of a product can not be designed for it to be bought less or not at all. Additionally, the R-imperative *Repurpose* is not integrated, as the repurposing of a product is not a type of use that a developer of a product can plan. The R-imperatives *Refurbish* and *Remanufacture* link the product life phases *Distribution* and *Usage* to *Production*. *Refurbish* is placed right from *Remanufacture* to indicate that the product is integrated back into *Production* at a later stage of the life phase. The arrows are summarized in order to make the flowchart clearer and to avoid overlapping arrows.

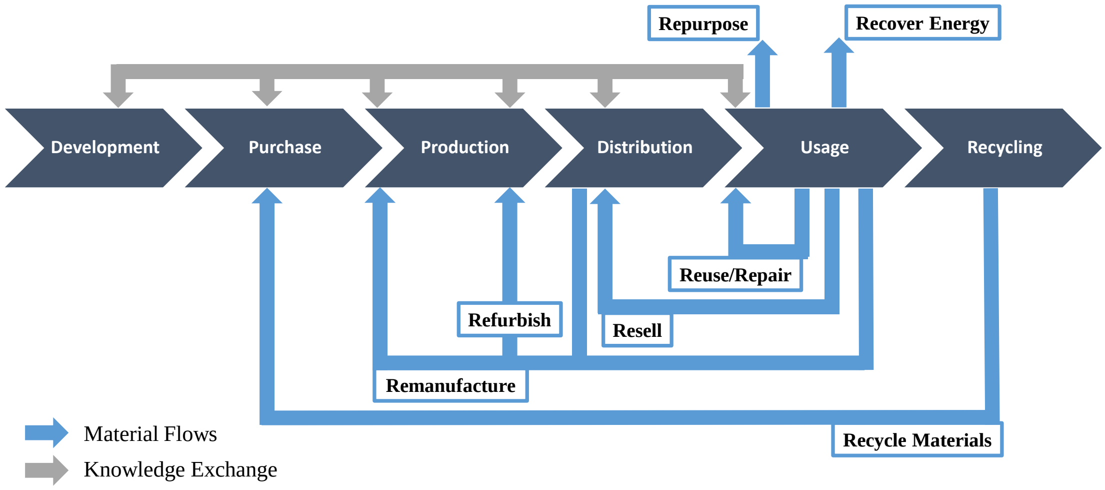

Figure 6. Product life phases and R-imperatives

4 DEVELOPMENT OF NEW MODULE DRIVERS

Sonego et al. (2018) have identified potential advantages in modular product designs concerning sustainability. To ensure that these advantages can be achieved via the use of the extension of the MFD or the LPM, the newly developed module drivers are based on these advantages. Since some of the advantages from Sonego et al. are affiliated to existing module drivers, not all of the identified advantages are embedded into new module drivers. The resulting list of module drivers is displayed in Table 2. There are no module drivers identified for the R-imperatives *Reuse* and *Resell*, since these R-imperatives do not need any alteration to the product. Additionally, to the module drivers, derived from Sonego et al. (2018), further module drivers were added for the R-imperatives. Furthermore, a module driver was identified, that is not associated with any of the R-imperatives. It is however not the aim of this publication to present a complete list of all possible module drivers associated to R-imperatives. Therefore, this list needs to be subject to further research in order to realise the full potential of sustainability in modular product architecture design via module drivers.

Table 2. Potential module drivers

R-imperative / product life phase	Module driver
Repair	Criticality
Refurbish	Resellability
Remanufacture	Life expectancy
	Degradation
Recover Energy	Process parameters
	Preparation
Recycling	Type of material
	Type of disposal
Development	Substitution components

Criticality aims to identify, whose end-of-life marks the end of life of the entire product. The goal of the module driver is to limit the reparation effort to one single module. *Resellability* aims to identify components, whose state might lower the value that the product has to a customer. *Life expectancy* aims to identify components, which will fail at roughly the same time. The goal of this module driver is to make the reuse of entire modules easier and limit the need to repair or exchange single components of a module. *Degradation* aims to identify components, which do not break but whose performance

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deteriorates over time. This module driver enables the use of used modules in different products with a lower demand in performance. *Process parameters* aims to identify components, which are burned within the same processes simplifying the recovering of energy. *Preparation* aims to identify the components, which need the same form of preparation before burning. *Type of material* aims to identify components made of the same material in order to enable the recycling of whole modules instead of single components and thus disassembly unnecessary. *Type of disposal* is doing the same at a wider perspective not clustering the same materials but the same type of disposal. *Substitution components* is the only module driver not related to any of the R-imperatives. Its aim is to identify components with a negative sustainability impact thus limiting the effort needed to exchange components for more sustainable alternatives to fewer modules. The module driver *Life expectancy* needs to be treated differently than the other module drivers. This is due to the fact, that simply identifying the components, that have a limited life expectancy does not lead to synergies in the module composition. However, the development of an additional adaptation of the method is not the goal of this contribution. Therefore, the further elaboration of the method is subject to following research.

5 APPLICATION TO AN INDUSTRIAL EXAMPLE

The newly developed module drivers are applied to an industrial example. For this purpose, a product family of pressure reducing valves with sensors is used, for which a modular kit is to be developed.
For this, the network diagrams of the individual life phases have already been developed with company representatives beforehand. The approach is based on the established LPM approach with the known module drivers. The network diagrams for the life phases *Purchase* and *Production* are shown in Figure 7 and . The added module drivers are highlighted by green boxes. On the right side of the figures the different modules are shown that were developed with and without the newly identified module drivers. The modules for the valves in the life phase Purchase are almost identical. The difference is, that without the focus on sustainability, the modules *Casted Module* and *Pressure Module* are purchased separately, whereas with focus on sustainability, they should be purchased as one module consisting of recycled materials (*Recycling Module*).

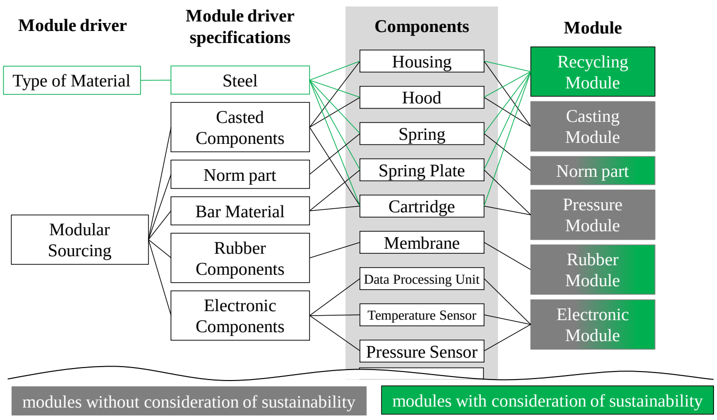

Figure 7. Network plan for the life phase Purchase

The changes for the modules for the life phase Production are different. For the production, the *Pressure Module,* containing the housing of the vales is split into two refurbishment modules. This is due to the different numbers of refurbishment cycles. For example, the casted housing could be refurbished more often than the rubber membrane or the wear-sensitive cartridge. The example of the industrial valves shows, that the newly developed module drivers have an impact on the modular structure and thus can improve the sustainability of products. The challenge in practice is the target conflict between the traditional goals of the product development, e.g. cost reduction or reduced time to market, and the goal to increase sustainability. This conflict has to be solved when concept alternatives are evaluated. In this example application more information about the product performance regarding the sustainability is needed to choose which modular product architecture should be further developed.

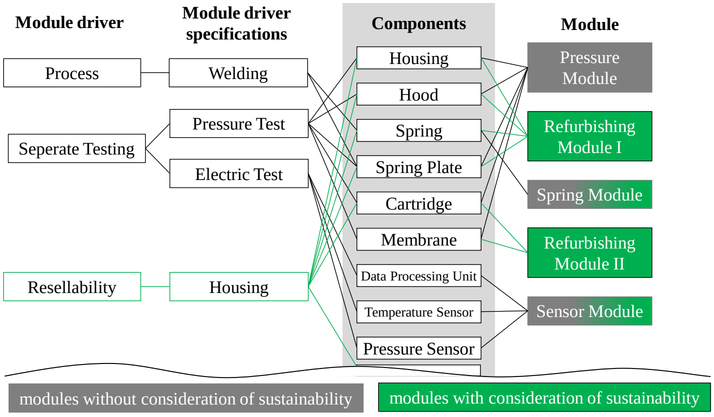

Figure 8. Network plan for the life phase Production

6 CONCLUSION

In this contribution, the R-imperatives are successfully integrated into the product life phases of the Modular Function Deployment. The Modular Function Deployment itself is adapted via the introduction of new module drivers. The resulting impact in the development of modular products is illustrated by the comparison of the modular structures of a product that were developed with conventional module drivers and the new set of module drivers respectively. The paper thus presents an approach that for the first time comprehensively integrates sustainability into the product life phases and this into the methods that are based on it.

7 OUTLOOK

Following this publication, the developed method needs to be used in a real development process. In addition, it needs to be applied to a system of higher complexity and with a more challenging sustainability impact. This is necessary to prove its applicability in more demanding development processes. Furthermore, the products developed in these projects and their use need to be monitored in order to evaluate the impact the method has on the actual sustainability impact. The results of these applications must be reflected back into the method and it must then be further elaborated. Since it was noticed, that the module driver *Life Expectancy* is not applicable within the method, there is a need to further adapt the method.

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