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Development of a Circularity Impact and Failure Analysis: Obsolescence and Recyclability Integration

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Abstract (300-500 words)

The application of the Failure Mode and Effect Analysis (FMEA) has been an established practice in systems engineering and engineering design for some decades. The benefit of applying FMEA is to raise engineers' awareness of potential risks related to a specific design configuration so that corrective actions can be preventively prioritized to avoid potential failure to happen. The work presented in this paper originates from the established practices of using FMEA and FMEA Boundary Diagrams in product development and extends the scope of analysis by integrating circularity considerations early on in the design process. Based on such rationale, the paper presents the first stage of the development of an approach named Circularity Impact and Failure Analysis (CIFA) aiming to become an integral part of a design for circularity strategy. The objective of the approach is to raise engineers' awareness about potential circularity issues in early design so that they can act accordingly to create more circular solutions. The paper presents the first results of the prescriptive work toward the development of CIFA, limiting the circularity considerations to the integration of obsolescence and recyclability considerations in the FMEA. The paper presents the logic and the rationale of the approach and exemplifies the application of the approach to the case of a bicycle V-brake.

Keywords: circular economy, systems engineering (SE), early design phase, FMEA, Circularity Impact and Effect Analysis.

1 Introduction

The necessity to move towards a more sustainable society is nowadays widely accepted in the research community and in the society as a whole. The existence of a strong relationship between how products are designed and manufactured and the achievement of consistent improvements in environmental and social sustainability is not questioned. There is an agreement that a move toward circular economy systems would strongly contribute to the achievement of the sustainable development goals defined by the United Nations (United Nations General Assembly, 2015). Research effort has been spent in defining what are the fundamental criteria upon which circular economy is defined and measured in industry (e.g., EASAC, 2016; Linder et al, 2017; Kalmykova et al., 2018; Moraga et al., 2019). To have a practical impact in everyday engineering work such high-level criteria need to be translated into a level of detail that influences engineers' design choices and preferences. Methods and tools to promote the development of circular systems have been proposed in literature both from a business development and a product development perspective (The Ellen MacArthur Foundation, 2015; den Hollander et al., 2017). However, the risk of any new method is to fail in the integration into the current well-established practices. This is particularly true in the case of complex product development and systems engineering projects, where hundreds or thousands of engineers, often globally distributed, rely on well-established and standardized methods for coordination and communication. In such cases, the capability for a new method and tool to seamlessly integrate into the current practice is highly relevant for its acceptance. One of those well-established methods is the Failure Mode and Effects Analysis (FMEA) described for the first time by the United States Department of Defence in 1949. The FMEA is commonly a worksheet where possible failure modes for functions or components are listed together with the possible causes, the probability to happen, the severity, and the possibility of detection of the failure. The arithmetic product of such parameters calculates a "risk priority number", suggesting an area of focus and encouraging engineers to define recommended actions and assign a responsible person to perform them, before running another loop of analysis. The work with FMEA is anticipated by the definition of the relevant components that are part of the product, or system, under consideration. This step is often facilitated by the use of the so-called FMEA Boundary Diagrams (also known as Boundary Diagrams or Boundary Block Diagrams) where engineers visually define the systems under consideration by drawing the boundaries of what is considered in the FMEA, and the type of relation or function that connects the components inside the boundaries among each other and with the closest component outside the boundaries of the system.

The work at the core of this paper originates from the established practices of using FMEA and FMEA Boundary Diagrams in product development. An approach to integrate obsolescence and recyclability consideration in FMEA is proposed as a first step toward the development of a Circularity Impact and Failure Analysis (CIFA), introducing the analysis of potential lack of circularity in the design as a complement to the traditional FMEA. The approach is meant to support engineers in the early design stages, by raising the awareness of the systems-level impact, in terms of circularity, of specific design decisions and configurations, thus reducing the risk for design modifications in later design stages. The approach considers obsolescence and recyclability in the frame of Design-for-Circularity as described by den Hollander et al. (2017) and follows the logic of traditional FMEA using the FMEA Boundary Diagrams as an input. The paper briefly describes the nature of the research approach in section 2, followed by a review of the use of FMEA when dealing with sustainability considerations, such as circularity. Section 4 describes the logic and rationale of the proposed approach, which is then exemplified through the case of a V-brake for a bicycle in section 5. Section 6 discusses the approach in the frame of the current literature and presents arguments for its further development in relation to its use in the design process as a complement to the FMEA.

2 Research approach

The problem definition at the origin of this paper is based on a research clarification activity performed through an extensive literature review in the field of circular product design and sustainable product development. Such findings have been combined with previous research results concerning the identification and quantification of design "ilities" in systems engineering (McManus et al., 2007; Bertoni et al., 2016). The proposed method has a prescriptive nature and the explanatory example through which it is described has been artificially defined, thus, although realistic, it does not reflect any specific implementation of the method in a real industrial case.

3 Failure Mode and Effect Analysis and sustainability considerations

The FMEA is a structured approach to identify the effects on the operations of a system caused by lower-level failures. The FMEA takes commonly the form of a tabular template to be filled in by engineers with the scope of identifying, prioritizing and limiting possible failure modes, both concerning the design and the process (respectively defined as Design FMEA and Process FMEA). The whole idea of FMEA is based on the assessment, either qualitative or quantitative, of the probability of a failure to happen, its potential severity, the possibility of the failure to be detected before happening, and the subsequent indication of the possible actions to undertake to avoid the failure. As highlighted in a review by Spreafico et al. (2017), both academia and industry have spent extensive research effort and filed a large number of patents applying, and further developing, FMEA with ad-hoc extensions and specific focuses. The review highlighted a slight overabundance of risk quantification solutions compared to real demand, with a concurrent misalignment of problem-solving proposals inferior to the real demand. A raised criticism of FMEA is its high focus on detailed incremental innovation and the inability to formalize more general problems in the approach. A common method to define the boundaries of analysis of FMEA is to use the so-called 'FMEA Block Diagrams'. The block diagrams define the components of the systems under investigations, their relationships in terms of data, physical, material, and energy exchanges, the external components that interface with the considered systems, and the type of relationships with such interfaces (see for instance Carlson, 2012). The FMEA Block Diagram clarifies the focus of the analysis and can be seen as a preparatory activity to Design FMEA (Carlson, 2012). Figure 1 shows an example of a simplified FMEA block diagram applied to a bicycle V-brake system, which will be later used as a case study to exemplify the application of the proposed approach.

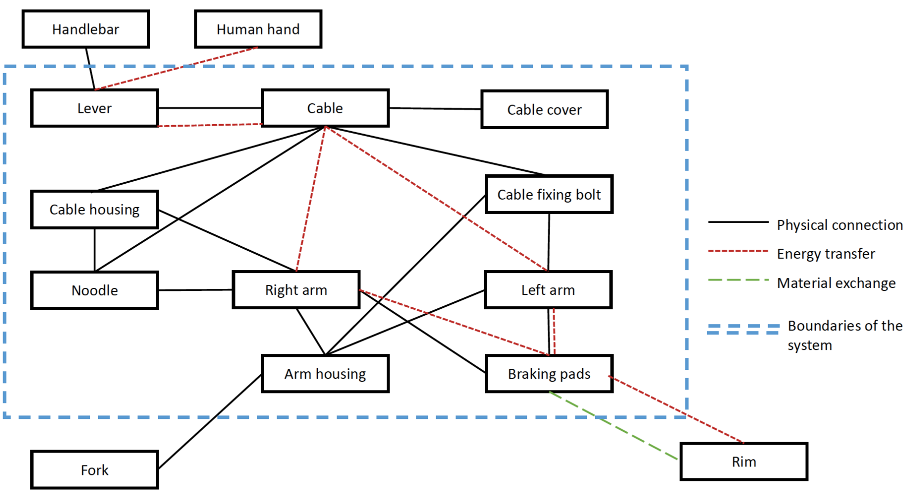

Figure 1. Simplified FMEA block diagram for a bicycle V-brake.

The idea of adopting the logic of FMEA to contribute to sustainable development has been previously discussed in the research literature. Lindahl (1999) presented a method called Environmental FMEA, previously proposed by Nilsson et al. (1998), meant to be used in the preliminary stage of product development using the results of a lifecycle assessment analysis and environmental function requirements as a primary input. Some years later, Nguyen et al. (2016) provided an example of FMEA application for sustainable manufacturing. However, despite the constantly growing environmental concerns, the idea of integrating sustainability or circularity considerations in an established method like FMEA at the detailed component level did not collect much interest in research. Nevertheless, a broad range of engineering methods have continued to flourish under the umbrella of Eco-design (e.g. Pigosso et al., 2013), Design for Sustainability (e.g. Bhamra, and Lofthouse, 2016), Design for environment (e.g. Sroufe et al., 2000), Sustainable Product development (e.g. Byggeth et al., 2007) and Design for Circularity (e.g. den Hollander et al., 2017). About the latter, research has focused on understanding what the features of a circular economy system are, and therefore, what kind of circular economy indicators can be introduced to measure the circularity, real or potential, of a product or a system. To this concern, the work by Moraga et al. (2019) proposed the identification of 3 scopes for circular economy indicators: Scope Zero aiming to measure physical properties for the technological cycle with no lifecycle thinking; Scope One similar to the previous but integrating a lifecycle thinking approach, thus considering aspects such as reusability, recyclability, and recoverability; Scope Two measuring burdens and benefits from technological cycles regarding environmental, economic, and/or social concerns in a cause-and-effect chain modeling. Similarly, the Ellen McArthur Foundation published a list of material circularity indicators at the product level and at the company level (The Ellen MacArthur Foundation, 2015). The importance of defining correct indicators for material circularity was also stressed by Pauliuk (2018) that, based on the analysis of the circular economy standards, underlined the importance of circular strategies to be monitored from a higher system perspective, to avoid defining indicators that would bring companies decisions in the wrong direction. This highlights the need to have the right indicators used in the correct context and with a suitable level of granularity based on the specific focus of the design activity. Focusing on the product design for circular economy den Hollander et al. (2017), investigated the fundamental differences between eco-design and circular product design arguing that circular product design is guided by the Inertia Principle as formulated by Stahel (2010). This prescribes product integrity to be the main design objective to be pursed and to be preferred to product recyclability, which will happen when integrity is no longer present. Based on such principle, the authors defined circular product design to be the combination of both design for integrity, aiming at resisting, postponing, and reversing obsolescence at product and component level, and design for recycling, aiming at preventing and reversing obsolescence at a material level. Additionally, den Hollander et al. (2017), also proposed a set of typologies of design approaches for product integrity defined as follow:

- Long Use – Resisting obsolescence: design for physical durability, design for emotional durability.
- Extended Use – Postponing Obsolescence: design for maintenance, design for upgrading.
- Recovering – Reversing Obsolescence: design for recontextualizing, design for repair, design for refurbishment, design for remanufacturing.

The approach presented in this paper is based on the above definition of circular product design by den Hollander et al. (2017) and adopts a restricted version of their typologies of design for product integrity. Furthermore, the approach is based on a selection of the indicators to diagnose product recyclability during product design proposed by de Aguilar et al. (2017).

4 Circularity Impact and Failure Analysis: a focus on obsolescence and recyclability

The approach presented in this paper complements FMEA with the consideration of an obsolescence scored based on design-for-integrity (such as proposed by den Hollander et al., 2017), and a recyclability score based on potential recyclability feature of the product, or system, under consideration. The approach uses as input the knowledge formalized in the product boundary block diagram and uses it to calculate an obsolescence impact score and a recyclability impact score, to be used to implement actions reducing the risk of failing to design the product in term of product integrity and recyclability. Such classification is adopted in line with the definition of product circularity by den Hollander et al. (2017) as described in section 3. Figure 2 shows the process to run the obsolescence and recyclability failure mode analysis. The following two sub-sections describe the activities in detail, followed by a section that exemplifies the analysis through its application in a simplified case.

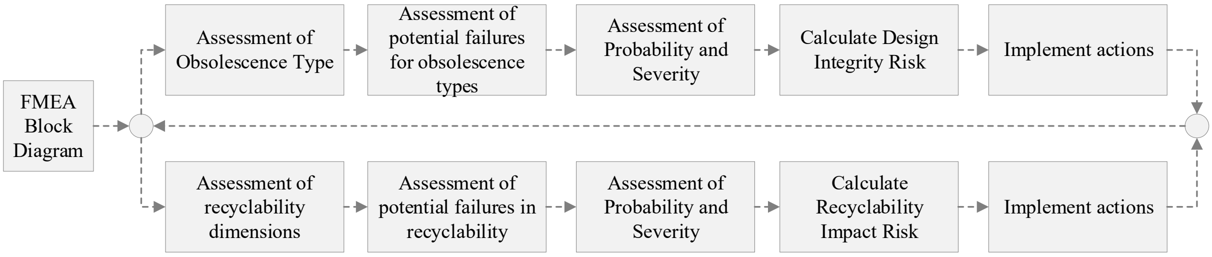

Figure 2. Proposed process for obsolescence and recyclability integration in the Circularity Impact and Failure Analysis

4.1 Obsolescence Impact and Failure Analysis based on product parts integrity

The first level of the analysis concerns the evaluation of potential actions to be implemented in terms of resisting, postponing, and reversing obsolescence. The list of system components as defined in the FMEA Block Diagram is imported in the CIFA worksheet. The upper part of Figure 3 shows the CIFA worksheet focusing on the product part integrity, detailing the criteria for each obsolesce strategy, i.e. physical durability, maintainability, upgradability, repairability, re-manufacturability, and usability in a different context. At this level, each component is assessed on a scale from 1 (very low) to 4 (very high) based on the criteria defined by den Hollander et al. (2017), that is, in terms of resisting obsolescence, postponing obsolescence and reversing obsolescence. The sum of the scores for each type of obsolescence (or the average of the scores for the type of obsolescence based on more than one criterion) gives a preliminary indication of the design-for-integrity score of each part. After this, potential causes of failure are listed and their probability and severity are assessed on a scale from 1 (very low) to 4 (very high). The Design Integrity Risk for each component is obtained as the product of each obsolescence type, calculated by multiplying the product of the probability and severity of an event with a number obtained by subtracting to five the average score of each related obsolescence type. It has to be noted that the decision to subtract to five the average score of each obsolescence type was taken to align the results to the traditional interpretation FMEA results, that is, low numbers as positive and high numbers as negative.

4.2 Recyclability Impact and Failure Analysis

The second level of CIFA concerns the evaluation of potential actions to be implemented to prevent possible failures in product recyclability. The analysis at this stage is not at a part or component level but rather as a system level, that means with consideration of all the parts defined as internal to the system boundaries identified in the FMEA block diagram. The lower part of Figure 3 shows the CIFA worksheet focusing on the recyclability of the system.

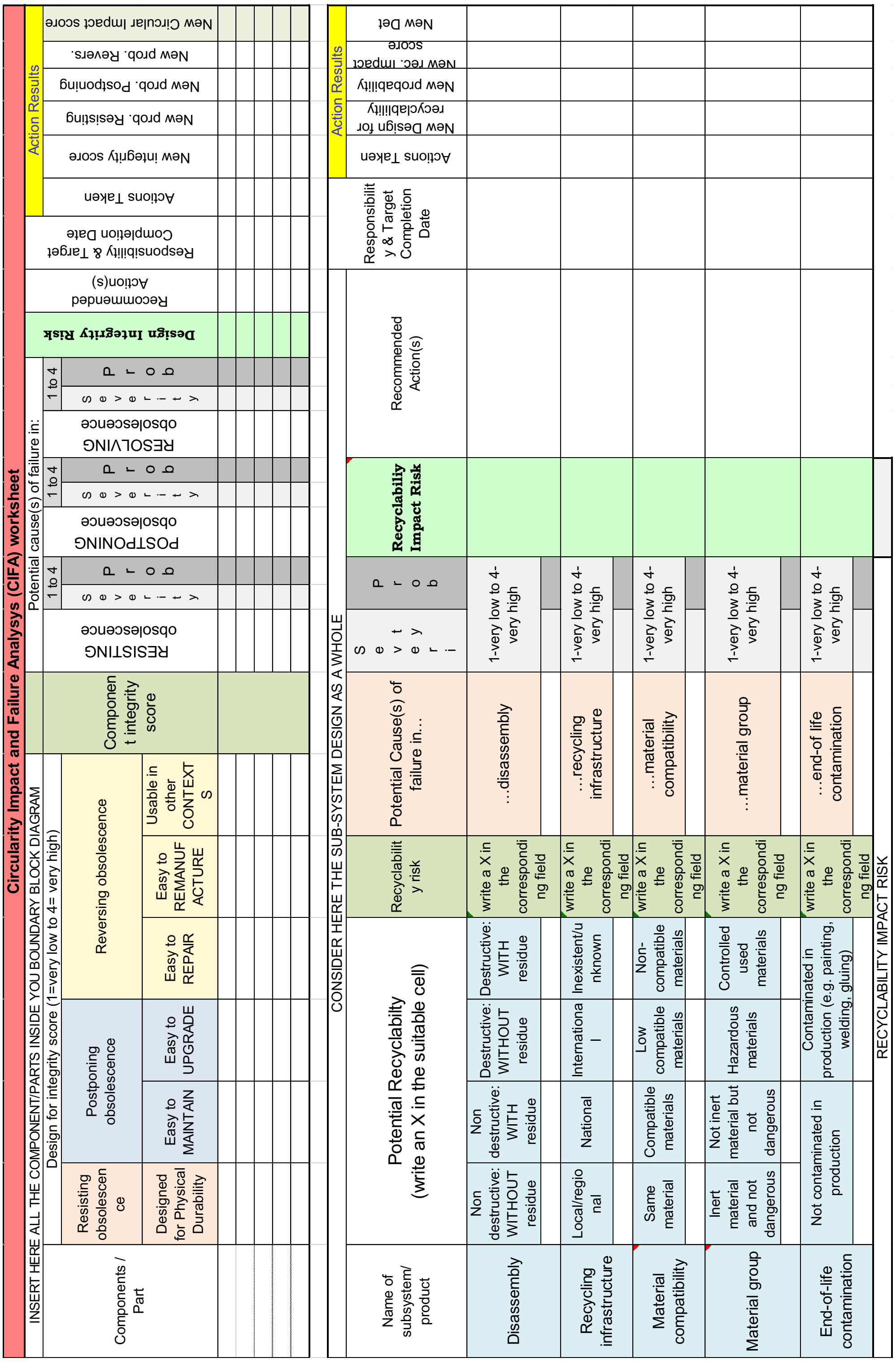

Figure 3. The proposed worksheet integrating obsolescence and recyclability considerations in the frame of a Circularity Impact and Failure Analysis.

The first step of the analysis consists of a checklist to determine the potential recyclability of the system upon 5 main dimensions, here listed based on the work of de Aguilar et al. (2017):

- Disassembly method of the system: non-destructive without residue, non-destructive with residue, destructive without residue, destructive with residue.
- Availability and accessibility of recycling infrastructure: local/regional, national, international, non-existent.

- Material compatibility of components: same material, compatible materials, low compatible materials, non-compatible materials.
- Type of material used in the systems based on the material group: inert material and not dangerous, not inert material but not dangerous, hazardous materials, controlled used materials.
- Contamination of product components to be considered in the end-of-life: Not contaminated in production, contaminated in production (e.g. painting, welding, gluing).

This activity is followed by the identification of the potential causes of failure in relation to the 5 listed recyclability dimensions, and the relative assessment of the probability of occurrence and severity. A score from 1 to 4 is assigned from the less problematic to the more risky recyclability condition, as described by de Aguilar et al. (2017), while concerning the end-of-life contamination either 1 or 4 is assigned for not contaminated or contaminated material. At this point, potential failures for the recyclability categories are listed in the central column of the worksheet and their probability and severity is assessed from 1 (very low) to 4 (very high). The product of the probability and severity multiplied with the recyclability risk for each of the five recyclability dimensions renders a final Recyclability Impact Risk for each dimension to guide the prioritization and the actions to be taken to prevent failures.

5 Example of application of the Circularity Impact and Failure Analysis on a bicycle brake

To exemplify the application of the obsolescence and recyclability integration in a Circularity Impact and Failure Analysis a reference case concerning the development of a V-brake for bicycles has been selected. A simplified version of an FMEA boundary diagram has been created has shown in Figure 1. Ten components have been identified as inside the boundaries of the system under redesign namely: lever, cable, cable cover, cable housing, noodle, right arm, left arm, cable fixing bolt, arm housing, braking pads. Those interface with the handlebar, the rim, the fork and the human hand that fall outside the boundary of the system and therefore are not considered in the CIFA. As a first step of the analysis, the list of components is imported in the worksheet and the principles of design for integrity are evaluated for each part. As shown in Figure 4, a score from 1 to 4 is assigned for each criterion concerning resisting, postponing, and reversing obsolescence. Based on that, a Component Integrity Score is calculated by multiplying the average score obtained for each obsolescence type. For instance, in the case of the lever of the brake (the first component in the analysis), a score of 20 is obtained thanks for a very positive evaluation of the Design for Durability criteria and the easiness to maintain and remanufacture the product. On the opposite the braking pads (the fourth component in the analysis) scores as low as 1.3 in component integrity given the negatives scores obtained in all the criteria related to physical durability, maintainability, upgradability, repairability, and re-manufacturability, with only one exception concerning the possibility of usability in a different context.

The upper-right side of the worksheet concerns the identification of the possible failure modes in obsolesce for each part and each obsolescence type. Potential causes of failures in resisting, postponing and reversing obsolescence are defined by the design team with the related qualitative assessment of probability to happen and severity from 1 to 4. For example, in the case of the lever, possible production problems might induce a failure in resisting obsolescence, this will most likely have a very low probability but potentially very high severity. Similarly, the bad quality of the material and the possibility of the introduction of a new braking technology, not using levers, might put the criteria concerning postponing and reversing obsolescence at risk, nevertheless, those cases are considered very unlikely to happen and with relatively low severity. On the opposite, the softness of the braking pad material, and the exchange of material and energy intrinsic in their use, induce low integrity scores.

Circularity Impact and Failure Analysys (CIFA) worksheet																	
INSERT HERE ALL THE COMPONENT/PARTS INSIDE YOU BOUNDARY BLOCK DIAGRAM								Potential cause(s) of failure in:									
	Design for integrity score (1=very low to 4= very high)								1-low to 4-high			1-low to 4-high			1-low to 4-high		
Components / Part	Resisting obsolescence	Postponing obsolescence		Reversing obsolescence			Component integrity score	RESISTING obsolescence	Severity	Prob	POSTPONING obsolescence	Severity	Prob	RESOLVING obsolescence	Severity	Prob	Design integrity risk
	Designed for Physical Durability	Easy to MAINTAIN	Easy to UPGRADE	Easy to REPAIR	Easy to REMANUFACTURE	Usable in other CONTEXTS											
Lever	4	4	1	1	4	1	20,0	Breakes due to problems in production	4	1	Bad material quality from supplier	2	1	New leverless brake technology make improsiible to reuse the component	1	1	60
Cable	3	3	1	1	3	4	16,0	Ossidation due to bad material	1	1	Cable not accessible for maintenace	1	1	Cable rusted and damaged due to high usage	2	2	56
Cable cover	2	3	1	2	3	1	8,0	Extreme wheater damages the materia (plastic)	2	4	Bad visibility of the component does not allow a proper maintenace	1	2	Very limited economical benefits in reversing obsolescence	1	4	1728
Braking pads	1	1	1	1	1	2	1,3	Pads glazing due to excessive heat	3	1	Pads melt and are not removable	3	1	Pads too consumed to be reused	1	4	2112
Arm housing	4	3	2	1	4	3	26,7	Brakes for stress due to problems in production	4	1	Bad visibility of the component does not allow a proper maintenace	1	2	New brake system make improsiible to reuse the component	2	2	187

CONSIDER HERE THE SUB-SYSTEM DESIGN AS A WHOLE										
Name of subsystem/ product	Potential Recyclabilty (write an X in the suitable cell)				Recyclability risk	Potential Cause(s) of failure in…	Severity	Prob	Recyclabiliy Impact Risk	Recommended Action(s)
Disassembly	Non destructive: WITHOUT residue	Non destructive: WITH residue	Destructive: WITHOUT residue	Destructive: WITH residue	1	…disassembly	1-very low to 4-very high		2	
	x					Difficult to separate components due to rust	1	2		
Recycling infrastructure	Local/regional	National	International	Inexistent/unknown	2	…recycling infrastructure	1-very low to 4-very high		4	
		x				Not available recycling technology	2	1		
Material compatibility	Same material	Compatible materials	Low compatible materials	Non-compatible materials	2	…material compatibility	1-very low to 4-very high		8	
		x				One of the material degrades to a level that makes it incompatible with others	2	2		
Material group	Inert material and not dangerous	Not inert material but not dangerous	Hazardous materials	Controlled used materials	2	…material group	1-very low to 4-very high		6	
		x				Contamination of hazardous materials while in use	3	1		
End-of-life contamination	Not contaminated in production		Contaminated in production (e.g. painting, welding, gluing)		4	…end-of life contamination	1-very low to 4-very high		12	
			x			Hazardous material leaks from the production process	3	1		
RECYCLABILITY IMPACT RISK									32	

Figure 4. Extract of the CIFA worksheet concerning the obsolescence and recyclability considerations in the case of the bicycle V-brake.

Based on such an assessment, a Design Integrity Risk is computed as described in section 4.1. In the case of the V-brake in Figure 4 both the cable cover and the braking pads scores high in terms of integrity risk, thus desired actions, responsibilities, and follow up controls should be defined accordingly.

The potential recyclability of the V-brake is assessed in the lower part of Figure 4, here the system considered consist of the sum of all the component inside the boundary defined in Figure

1. In the second column, the potential recyclability of the system is assessed based on engineering expertise and knowledge, marking the corresponding cell with a ‚x‘. In this case, the disassembly of the brake could happen in a non-destructive manner without creating residues, the recycling infrastructure is available at a national level, materials are compatible, non-inert but no dangerous, and there is no contamination in production that might affect the end of life of the system. In this case, the results proved the V-brake to have a low risk in recyclability for what concerns the recycling infrastructure and the disassembly (respectively 4 and 2 in Figure 4), while having a higher Recyclability Impact Risk concerning the end-of-life contamination.

6 Concluding remark

The application of the Failure Mode and Effect Analysis has been an established practice in systems engineering and product development for some decades. The benefit of applying FMEA is to raise engineers' awareness of potential risks related to a specific design configuration so to preventively prioritize corrective actions to avoid potential failure to happen. This paper proposes the extension of the focus of FMEA adding the consideration of component obsolescence and systems recyclability as two of the relevant levels of analysis needed to address the need for more circular system design. It is inspired by the definition of the Environmental FMEA by Lindahl (1999) and represents an iteration toward expanding such an analysis toward the principles of the circular economy. Concerning the concept of circularity and circular product design, the approach is based on the definition proposed by den Hollander et al. (2017), which was found to be the most suitable for the integration into a failure mode analysis. Nevertheless, as mentioned in section 3, the literature on circular product design is vast and quickly evolving, and different approaches have been proposed and validated in literature. To this concern, the consideration of obsolescence, in the form of product integrity and recyclability, has been presented as the first two steps toward the development of a Circularity Impact and Failure Analysis. The development of a CIFA that encompasses multiple and cross-disciplinary circularity levels, e.g. including a broader consideration of strategical, tactical, and operational sustainability, is intended to be the next step toward the development of a more consistent and approach for circularity integration. Such development will need to consider long term sustainability strategies to be traded off with circularity strategies, that is, accounting for the possible sub-optimization of sustainability performances induced by the adherence to a design for circularity strategy.

The template and the case application on a bicycle V-brake presented in this paper, are prescriptive results from the research activity and are not substantiated by extensive validation about applicability, usability, and usefulness of the approach. Such validation is planned as a future step in the research activity that will encompass the simulation of design sessions in a controlled environment, followed by verification in real industrial settings.

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