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PRODUCT FAILURE: A LIFE CYCLE APPROACH

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ABSTRACT

The aim of this paper is to introduce a life cycle perspective on the notion of failure of engineered products. Usually failure is seen as an event that can occur during the utilization stage of products. Moreover, most definitions describe failure in terms of manifest termination of expected performance. The life cycle perspective expands this view by including failures occurring outside the utilization stage, and offers a categorization of phenomena that are arguably also taken as failures in engineering. The paper starts by considering previous attempts to take the life cycle into account when dealing with product failure. A definition of failure suitable for the life cycle approach is proposed and applied to categorize a number of case stories and examples of failure occurring in different stages of the life cycle, confirming the engineering credibility of the approach. Moreover, it shows that the life cycle approach affords applying the notion of failure to events that can occur after the products are removed from service and are related to their sustainability.

Keywords: Failure, product life cycle, manufacturing, maintenance, retirement, sustainability

1 INTRODUCTION

Failure of a product is typically assumed to occur during use. For instance, Becker et al. [1] notice that many failure analysts – like the majority of people – are inclined to think that "all failures could be divided into one of two major causes: abuse or defects". In the first case, a well-functioning product fails because the user places demands on the product exceeding the operational conditions for which it is designed. In the second case, the user has done nothing wrong and the product itself is discovered to be inadequate. In both cases, the scenario in which failure takes place is the utilization stage. Sometimes other stages of the product life cycle may enter the equation as well, for instance, when the failure is attributed to a defective product and the quest for the origin of the defect is carried on. The design stage and manufacturing stage then enter the equation but only as possible sources of the causal influence that let the failure to occur, later on, during usage. The utilization stage can also be the origin of that causal influence, e.g., when the product is abused by the user, yet is the only stage where failure is situated.

If the expression "F(X) because of Y" is introduced as shorthand for "the product is failing in stage X of the life cycle because of factors originating in stage Y", then the typical view of failure can be captured by the following expression:

F(U) because of Y (1)

According to the traditional view, the only admissible value for 'X' is 'U', which stands for the utilization stage. An instance of manufacturing failure that is to say, of a failure localized in utilization due to a manufacturing issue, will be described as:

F(U) because of M (2)

(Where 'M' stands for manufacturing).

The aim of this paper is to make plausible that product failure may occur during each stage of the life cycle and that the causes of failure may relate to each of the preceding stages or to the current stage itself. The life cycle approach to failure, then, could be represented by means of the expression:

F(X) because of Y (3)

In (4), both 'X' and 'Y' variables can assume multiple values.

In the next section, it is shown that in the literature authors have anticipated the idea that failure can occur in other stages of the life cycle besides utilization. In Section 3, the typical view on failure is spelled out in more detail and a life cycle model for representing the various routes to failure is introduced. Section 4 deals with the proper way of defining failure in the life cycle approach. In

Section 5, the approach is applied to a number of case stories and examples related to various stages in the product life cycle. Some of these cases, although located outside the utilization stage, are easily reconciled with the traditional view, e.g., structural failure during construction. However, it is also shown that the life cycle approach expands the traditional view introducing the possibility of product failure related to sustainability, e.g., failure during retirement. The paper concludes in Section 6 summing up the argumentation and anticipating directions for future developments.

2 TOWARDS A LIFE CYCLE APPROACH TO FAILURE

One way of introducing the life cycle approach to failure is by noticing that the user is not the only stakeholder in the life of a product; there are other stakeholders and for them the product may fail as well. The International Standard on systems and software engineering ISO/IEC 15288 [2], for instance, claims that besides the customer there are other stakeholders "who have a legitimate interest in the system throughout its life cycle". Although the standard does not address the issue of product failure in detail, a section about the Risk Management Process is present in which it is clearly stated that risks must be addressed systematically "throughout the life cycle of a system product or service" and this implies taking into account other stages besides operation, like acquisition, development, and maintenance.

A similar line of reasoning can be found in some publications on Failure Modes and Effects Analysis (FMEA), e.g., [3], [4]. FMEA is a systematic, bottom-up, design support tool to identify and assess potential product failures. In short, it consists in examining, for each component of the product, the causes, effects and remedies of potential failures before the product is actually produced and put into operation. The aim is to "maximize the satisfaction of the customer by eliminating and/or reducing known or potential problems" [3]. Stamatis [3] notices that the usefulness and effectiveness of the FMEA process depends on how "the customer" is defined. Stamatis recommends avoiding the restrictive approach according to which "the customer is thought of as the end user". Such an approach reduces the scope and causes the FMEA to address only potential failures affecting the satisfaction of the user. For wider and more effective results a customer also "may be viewed as the subsequent or downstream operation as well as a service operation".

The fact that failure is not confined to the utilization stage is also well known in civil engineering since it may happen that buildings fail during construction. A notable case is the failure of Quebec Bridge in 1907 [5]. It was determined that the bridge collapsed during construction because of improper design such that the bridge was not capable to withstand its own weight. Structural failure during construction may also occur because of shortcomings related to the construction process itself. According to the results of the investigation, that was the case in the collapse of the Willow Island cooling tower in 1978 [6]. The scope of the Willow Island project was to build two concrete cooling towers for a coal-fired power plant. The design of the towers and the construction technique were both fairly common and well known to the building company which had already successfully built thirty-six similar towers in the preceding seven years. On the day of the disaster, a team of workers were pouring concrete about 60 m aboveground. The platform on which they were standing was anchored to the concrete that had been poured only twenty-four hours before. This reduced interval was not sufficient for the concrete to reach enough strength as to support the platform. When a bucket filled with one ton of concrete was lifted to the platform, the anchorages ripped loose and the platform fell to the ground killing all fifty-one workers that were standing on top of it.

In a paper about failures of polymeric materials, material scientists and failure analysts Ezrin and Lavigne [7] observe that failures "can occur for practically any polymeric material in various ways and at various stages of manufacture, assembly and service". Also Viswanadham and Singh [8], in a book about failure of electronic packages, state that failures "can occur during any of the different stages of the product cycle with the exception of design stage. These include manufacturing process steps, end of line tests, screening tests prior to shipment of the product. Failures can also occur during shipment of product to the customer or in the customer environment".

The works briefly described above illustrate that the life cycle approach has, to some extent, already been anticipated. The aim of this paper is to articulate the approach by arguing that it is tenable and by showing that it implies a wider notion of failure than the traditional one.

3 THE TYPICAL VIEW ON FAILURE

The typical view on failure is summarized in Figure 1, in which the product life cycle is made of three successive stages and the possible causal routes are represented by three solid arrows. The arrows can originate from any stage, but they invariably point, as the localization of failure, to the utilization stage.

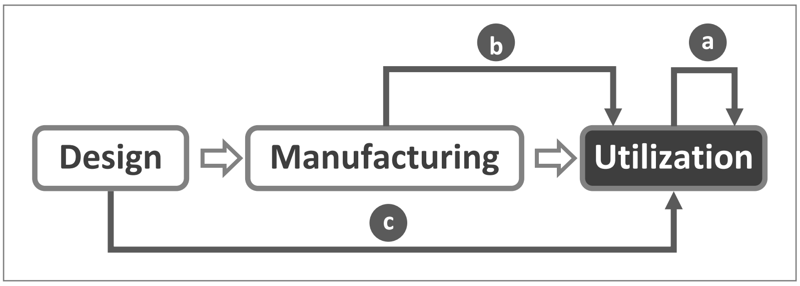

Figure 1. According to the typical view failure is limited to the utilization stage

The arrow marked with (a) in Figure 1 represents cases of failure during the utilization stage due to product abuse, that is to say the product is used beyond the operational parameters anticipated during design. This can result in damage being done to the product (e.g., it is exposed to temperatures beyond the melting point of some components) or simply in lack of expected performance. As an instance of the latter, on October 2006, mountaineer Neal Mueller wrote a piece for the Washington Post [9], [10] complaining that his Apple iPod failed to play his favorite song once he had managed to climb until the top of Mount Everest. Apparently, in writing his complaint Mueller was unaware that the product specifications for the iPod state that operating temperature should be in the range between 0-35 °C and the altitude should be below 3000 m. Both conditions are violated on the top of the Mount Everest.

Arrow (b) represents cases of failure stemming from manufacturing defects, also known as “manufacturing failures” that can be defined as failures “caused by poor workmanship or inadequate manufacturing process control during equipment construction” [11]. An instance of this kind of failure affected some items of the Nokia N97 cell phone [12]. Users complained that pictures taken with the camera with which the phone is equipped contained artifacts. Upon investigation, it was discovered that the artifacts were determined by scratches on the lens of the camera. Of course, lenses may be damaged during use because of incidents or improper handling of the phone, in which case the manufacturer will be exempted. However, for the N97 phone it was determined that the scratches were caused by particles of dirt and dust that became entrapped between the lens and the lens-cover. Nokia has admitted that because of a defective manufacturing process in a certain number of phones “the lens cover may have been mounted too close to the lens glass”, allowing the scratching particles to become entrapped and to exert their damaging action each time the user is to slide the cover for taking pictures.

Arrow (c) designates failures due to inadequate design, also known as “design failures”. According to Dodson [11], design failure is “any failure that can be traced directly to the design of the equipment; that is, the design of the equipment caused the part in question to degrade or fail, resulting in an equipment failure”. Arguably, Dodson’s definition is too restrictive for it seems to neglect the possibility that a physically intact and properly manufactured product is unable to perform as specified because of a design shortcoming. The media have deserved a lot of coverage to a recent case that, allegedly, fits this description: the so-called “antenna gate” involving another Apple gadget, the iPhone 4. Admittedly the issue is still disputed and conclusive evidence is lacking. Nevertheless the case provides a good first impression of how a design failure may look like. The magazine *Consumer Reports*, a well-known source of product reviews in the US, conducted a controlled experiment and claimed it would not recommend the iPhone 4 because of a design flaw with its antenna. The experiment has shown that the phone has problems of signal loss. More precisely, if the phone is held in a way that the user’s “finger or hand touches a spot on the phone’s lower left side – an easy thing, especially for lefties – the signal can significantly degrade”. According to *Consumer Reports* the problem lies with the design solution adopted by Apple engineers that makes the antenna to serve also an aesthetic function as the phone’s outer rim. The test proved that electrically insulating the sensible spot, e.g., with a small piece of duct tape, significantly reduces the problem of signal loss. In fact, Apple has decided, as a temporary fix, to provide the customers with a free rubber frame that insulates the hands of the user from the antenna.

4 A DEFINITION OF FAILURE FOR THE LIFE CYCLE APPROACH

In order to proceed with the analysis of the life cycle approach, a sound definition of failure is needed. Of course, the definition must be able to deal with failure during the utilization stage, which has been the paradigm for the notion of failure so far, besides addressing failures during other stages. A survey [13] of the literature performed in a previous stage of this PhD project has revealed that several definitions of failure are available. Some definitions have a special focus on the material properties of products and components and their structural integrity. A representative definition is the following: “Failure: Cessation of function or usefulness of a part or assembly. The major types of failure are corrosion, distortion, fracture and wear.” [14]. Other definitions have a broader scope and look beyond physical properties. Leonards [15], for instance, defines failure as “an unacceptable difference between expected and observed performance” therefore introducing the possibility of failures that occur independently from material alterations to the product, for instance because they stem from inadequate design.

Two assumptions appear to be shared by almost all definitions. The first assumption is that failures imply manifest termination of proper functioning; the second is that the product functionalities taken into account are only those relevant for the utilization stage. However, as argued in Section 2, the user is not the only stakeholder in the life cycle of a product. Other stakeholders have a legitimate interest in the product’s behavior throughout the life cycle and what is at stake is not simply the proper functioning of the product, but the product’s ability to consistently meet predetermined requirements. Discussing the issue of product performance during assembly, Whitney [16] notices that when problems emerge “the basic assumption […] is that if the assembly reliability is low, either the *product is at fault* […] or there is some variation in the assembly process” (emphasis added). The fact that the product is at fault means that it is falling short of the assemblability requirements. And the same can be said for manufacturability requirements, maintainability requirements, and so on. In the most serious cases, the product can completely lack the needed properties and the stage cannot be completed at all. More commonly, the stage can be completed, but the product failure causes time and cost overruns, rework, increased waste, and so on. Therefore, a life cycle approach calls for a shift of focus from the manifest lack of proper functioning to the product’s inability of meeting requirements that are meant as a response to the needs of multiple stakeholders.

Stamatis [3], in his book on FMEA mentioned above, provides a definition of failure that is suited for the life cycle approach. According to his definition failure is the “inability of the system, design, process, service, or subsystem to perform based on the design intent. […]. This inability can be defined as both known and potential”. A distinguishing feature of the definition is the term “design intent” which is indeed more appropriate than the term “requirements” that has been used so far in this paper. The reason is that product properties like manufacturability and assemblability are context dependent. It may happen that the same product, designed by company A, would be easily manufactured by using the machinery and expertise available at company B while it would be hardly manufacturable by company C which has different expertise and machinery. What counts for failure is design intent. If the company A, possibly out of cost considerations, decides to close the deal with company B, then, when the product will fail during manufacturing, the design decision is the culprit and not the manufacturing process.

In the rest of this paper, the notion of failure will be defined in accordance with Stamatis definition.

5 FAILURE IN X

So what happens if one generalizes failure from its user centered perspective? In this section, the life cycle approach to failure will be discussed in more detail providing relevant examples and case histories. It will be shown that the approach is compatible with standard engineering descriptions of failure events. On top of that, at the end of this section, it will be shown that, according to the life cycle approach a number of other phenomena can be seen as failures.

The heading of the section borrows from the well-known engineering terminology “Design for X”, where X is a variable that can have many values, like manufacturing, assembly, usability, and so on. In the expression “Failure in X”, or “Failure during X” the values are the life cycle stages the product goes through, e.g., manufacturing, assembly, utilization, and so on.

The aim of the approach proposed in this a paper is to be applicable to all kinds of products, whatever complicated their life cycle is. This raises the question of what life cycle model to adopt since many different models have been proposed in the literature. In systems engineering a life cycle model is a "decision-linked conceptual segmentation" [17] used to represent and manage technical and business decisions during the life of product, from the initial conceptualization through its eventual retirement. Therefore, the number and the sequence of stages in a life cycle model depend not only on the product's physical features, but also on the decisional procedures of the organization. Given two structurally and functionally very similar products designed and produced by two different companies, their respective models may look rather different. As a result, there is no unique model that is able to accommodate all kinds of products. For instance, ISO/IEC TR 24748-1 [17] provides eight examples of life cycle models. The simplest one is a model for natural entities sold as products, which is constituted of four stages, i.e., acquisition, development, exploitation, retirement. The model for a facility is made of six stages, namely: rendering, structure and site design, permitting, construction, operation and maintenance, retirement. While conceding that providing a universal model is not feasible, ISO/IEC 15288 chooses as the paradigm of a system's life cycle a model composed of the following six stages: Concept, Development, Production, Utilization, Support, and Retirement. This should not be taken as normative, of course, and the number and arrangement of stages can be modified, or sub-stages can be included depending on the circumstances.
A model made of the following five stages will suffice the needs of this paper: design (D), manufacturing (M), utilization (U), maintenance (Mt), retirement (R). The categorization of failures according to the life cycle approach will start examining examples of failures during the manufacturing stage.

5.1 Failure in manufacturing

Sudhakar and Paredes [18] investigated the case of automotive metal bearings failing in manufacturing. The bearings were produced by soldering a layer of a copper alloy onto a steel backing. The failure investigation started after a number of bearings were found showing clear signs of copper detachment and cracking after soldering (Figure 2).

Figure 2. Metal bearings failure in manufacturing. Detachment areas shown by arrows. Source [18]

Stamatis definition correctly classifies the detachment as failure since the design intent was to produce bearings in which the copper layer is firmly bonded to the steel substrate. Sudhakar and Paredes determined that the cause of failure was the manufacturing process itself; more precisely, it was due "to improper sintering time and temperature that did not allow the diffusion process to complete". Using the formalism introduced above, the failure can be represented by means of the expression:

$$F(M) \text{ because of } M \qquad (4)$$

A product may fail in manufacturing also because of inadequate design. Let us consider a product that is made of tempered glass. Tempering is a thermal process that is performed in order to confer better mechanical properties to glass for applications like windowpanes, glass doors, tables, and so on. The tempering process introduces internal stresses within the material such that it cannot be reworked after tempering or it will shatter into pieces. If, usually for installation purposes, holes have to be drilled into the piece of glass, the drilling must be made before tempering. Moreover, the internal stresses that will be created by the thermal process dictate a number of restrictions about holes placement and dimensioning the designer must be aware of. Some of these restrictions are shown in Figure 3. If these restrictions are not obeyed, the building up of internal stresses during tempering will cause the glass to shatter into pieces. The product will fail during manufacturing and redesign is needed in order to overcome the problem.

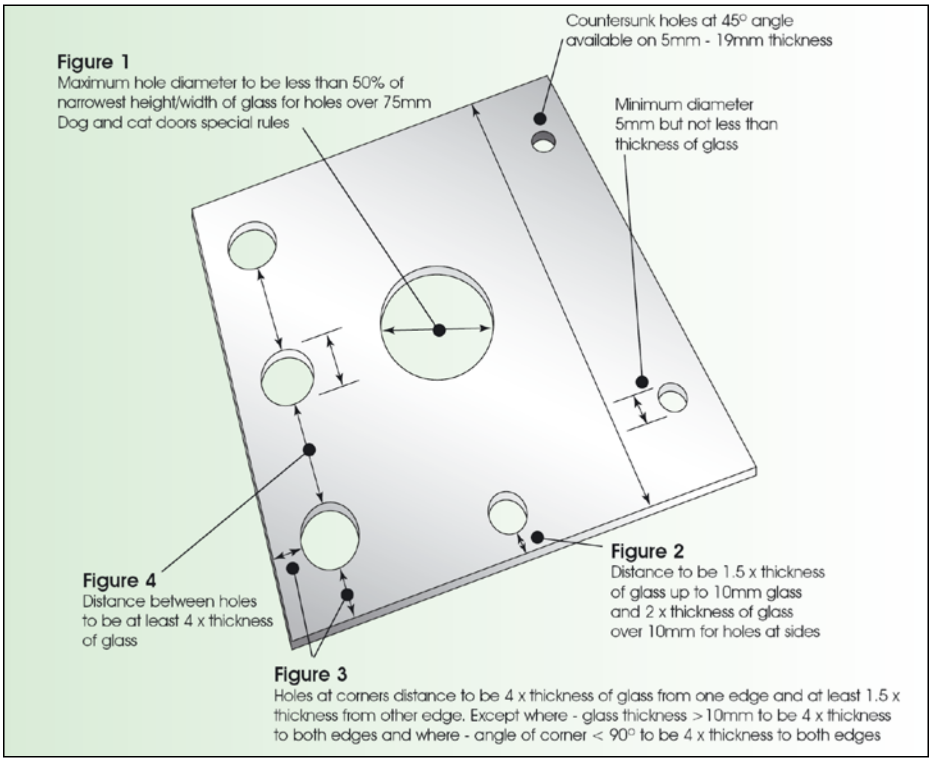

Figure 3. Example of restrictions in hole's placement in tempered glass. Source [19]

The glass example is a relatively innocuous one. In the building industry, however, failure during construction is a serious issue since the consequences can be severe and construction is also the stage in which structures are most vulnerable. The Quebec Bridge collapse mentioned above is an eloquent illustration of a failure during construction due to inadequate design.

Given that providing the product with the ability to be properly manufactured is part of the design intent, Stamatis definition would apply correctly to the tempered glass example and to similar kinds of failure. These will be represented by the following formula:

F(M) because of D (5)

Figure 4 provides a graphical illustration of the two types of failure in manufacturing seen above.

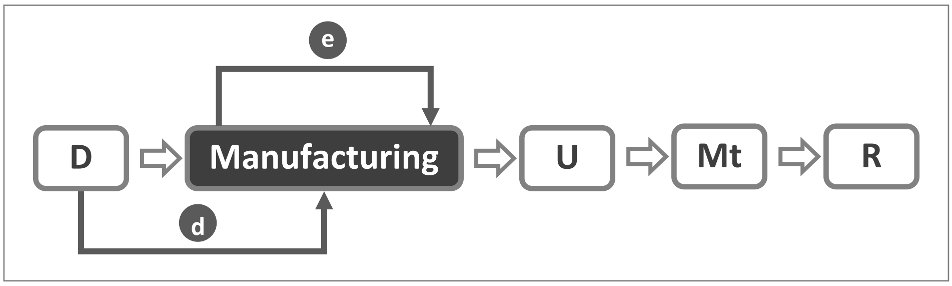

Figure 4. Failure in manufacturing.

Arrow (d) represents failure due to inadequate product design, and arrow (e) represents failure in manufacturing due to inadequate manufacturing process.

5.2 Failure in maintenance

Design intent with regard to the maintenance stage is that the product will be inspected and reconditioned according to established procedures and within acceptable cost and time limits in order to reintroduce it safely back to service. Extending the life cycle approach to failure similarly to what has just been done for the manufacturing stage will result in the following routes to failure in maintenance:

F(Mt) because of Y, with Y either D, M, U, Mt (6)

Figure 5 summarizes the four possible routes to failure in maintenance.

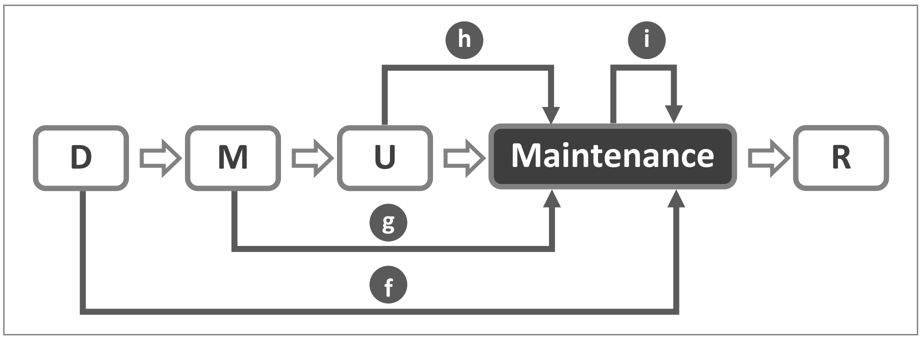

Figure 5. Failure in maintenance

An example of failure in maintenance due to maintenance errors, arrow (i), can be found looking at power supply networks. Investigating the issue of reliability of these networks, Neumann and Weber [20] and Song and Dong [21] mention explicitly the possibility of failure during maintenance. More precisely, Neumann and Weber describe the eventuality of failure during maintenance being "caused by wrong operation related to the maintenance, e.g., unnecessary disconnection of reserve component in operation or wrong testing of protection system".

As an instance of failure in maintenance due to poor design, arrow (f), let us consider an example from aviation. McDonnell Douglas was criticized for the lengthy and unsafe procedures needed to perform inspection and lubrication of the engine attachments on the DC-10 [22], [23]. The procedure demanded first the engine removal from its pylon and then the pylon removal from the wing. Besides the complexity of the operation and the time expenditure, a major concern was that more than seventy disconnections of fuel lines, hydraulic lines, electrical cables, etc. were needed. Maintenance and safety engineers know that every disconnection is a factor of risk because damage can occur or a mistake can be made during reconnection.

A failure because of inadequate manufacturing, arrow (g), might occur in the event that a defective component gets stuck and cannot be removed and inspected according to stated procedures. The failure is only partial because alternative techniques will allow maintenance personal to complete the task. Still the product will fall short of design expectations about its performance during maintenance stage.

Route (h) occurs when a product fails during maintenance because of circumstances related to usage, like exposing the product to environmental conditions, e.g., operating temperatures, beyond the specifications and resulting in unexpected alterations to the product such that it cannot be repaired.

5.3 Failure in retirement

The examples and case histories discussed so far can be rather easily reconciled with the traditional view on failure. Indeed, a half constructed bridge collapsing is a clear instance of structural failure as well as a power outage because of wrong maintenance operations. The life cycle approach, however, contemplates the possibility of product failure occurring also after the useful life has expired.

Sooner or later products are removed from service. Depending on the type of product and the applicable regulations and standards, some products are disposed of, others are recycled, still others are reused, and so on. In this paper the term "retirement" (R) will be used for indicating this stage. This is also the term used by the ISO/IEC 15288 [2] and ISO TR 24748 [17] standards, the latter describing the expected outcome of the retirement stage as the decommissioning of the system-of-interest "including disposal, refurbishing, or recycling, in accordance with applicable health, safety, security, privacy and environmental laws and regulations".

As seen for the previous stages, a product may fail during retirement for reasons related to anyone of the previous stages in the life cycle, or because of circumstance related to the retirement process itself. That could be captured by means of the following expression:

$$F(R) \text{ because of } Y, \text{ with } Y \text{ either } D, M, U, Mt, R \quad (7)$$

The five possible routes are represented in Figure 6.

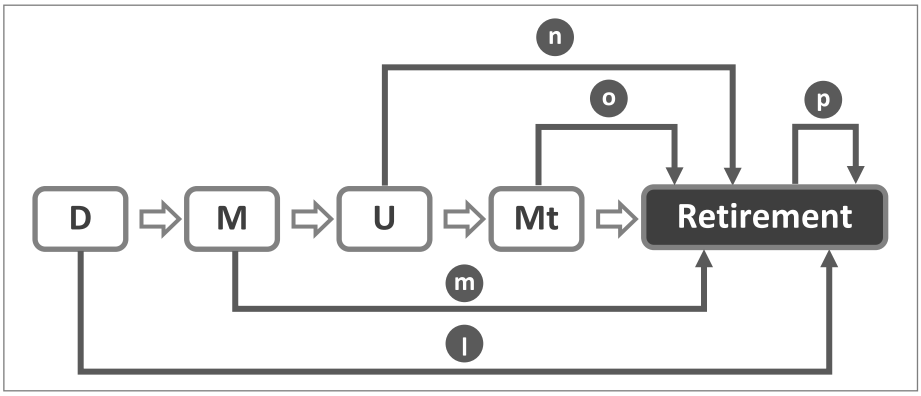

Figure 6. Failure in retirement

Due to the introduction of environmental standards and regulations and to consumer concerns for the environmental impact of products, companies are increasingly looking for improving the overall sustainability performance of their products. All stages in the life cycle are affected. For the retirement stage, one of the aims is to reduce as much as possible the amount of waste that is landfilled. The European Directive 2000/53/EC [24], for instance, mandates that “no later than 1 January 2015, for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95 % by an average weight per vehicle and year”.

Recycling of a complex product such as a car is a multistep process. First the product is disassembled, then extraction of material fractions take place, and then the output fractions are supplied to material recovery processes. Design solutions can influence efficiency and effectiveness of all these processes. A failure in retirement due to design, arrow (l), might occur because the product has too many small components. In a study on design for recycling of computer enclosures Masanet and Horvath [25] have found that “PC enclosure components with a mass of 25 g or less would be discarded (a common practice for small plastic components)” and thus that the demanufacturing waste fraction of the product might rise beyond requirements.

Route (m) represents failure in retirement due to circumstances related to the manufacturing of the product. Consider the process of recovering copper from printed circuit boards [26]. The boards are put into a converter where the plastics are burnt and the metals are retained. If, for a mistake during manufacturing of the plastic support, toxic additives were introduced into the mixture, toxins will be emitted during the recycling process eventually causing the failure of the retirement process to meet the emissions requirements.

The user can be instrumental in causing product failure in retirement, arrow (n), by not returning the product to service centers. Behrendt et al [26] notice that this is a rather common situation for small appliances “which, because of their size, are generally disposed of together with household waste”. If part of the design intent was to achieve a predetermined level of recycling through a take back strategy, the lack of user cooperation may cause the product to fall short of the recycling requirements.

Maintenance, route (o), can alter a product and render it unfit for the planned retirement procedure. For instance, repairs made by gluing or welding of components that were meant to be bolted will make disassembly more difficult or impossible.

Finally, a product might fail during retirement because of circumstances related to the retirement process itself. On June 15, 2010 a bridge that was being dismantled collapsed in Naugatuck, Connecticut, seriously injuring one worker [27]. The investigation is still under way, but one of the hypotheses under scrutiny is that the collapse could have been caused by a shortcoming in the dismantling process itself.

6 CONCLUSION

Most of the engineering characterizations of failure are based on the scenario of products failing during the utilization stage. Within these characterizations, product life cycle stages prior to use are mentioned only because of their causal role in bringing about the failure during the use stage. For instance, “manufacturing failure” refers to a product failure occurring during the use stage that is allegedly caused by a defect or flaw introduced during manufacturing.

This paper argues for a broader notion of failure according to which product failure may occur in any stage of the life cycle. This view is in accordance with current system and software engineering best practices based on life cycle management, like the recent International Standard ISO/IEC 15288 and the related guidelines ISO/IEC TR24748-1. A fundamental assumption of these practices is that product development has to take into account the requirements of multiple stakeholders. Customer satisfaction is the fundamental objective in developing a new product; however, stakeholders whose stakes lie in stages other than use dictate important requirements that the product is expected to meet as well, for instance requirements related to manufacturability, assemblability, installability, and so on. The life cycle approach developed in this paper anticipates the possibility of products failing during any stage in their life cycle, including failures that may occur after a product is removed from service. The latter are progressively becoming an area of major interest for engineers and designers because of strict regulations about product performance in recycling, reuse, disposal, and so on.

In this paper, it has been argued that the definition of failure provided by Stamatis [3] is better suited to the life cycle approach than other definitions which are linked to the traditional view on failure. According to the latter, the main criterion for assessing failure is the manifest termination of proper functioning. Instead, according to Stamatis, the main criterion is the product’s ability to perform based on design intent. This definition has some relevant consequences on the categorization of failure events that have not been discussed in this paper and that are the subject of ongoing research. Design solutions determine fundamental product capabilities like manufacturability, assemblability, etc. that will be shared by all items of a product. Therefore, inadequate design usually causes total failure, which affects all items of a product. On the other hand, failures due to process variations, e.g., manufacturing failure or abuse during utilization, affect a limited number of items. Another consequence of the definition is that, depending on the nature of the violated requirement, it is possible to distinguish between fatal failures, in which case the product is unable to complete successfully a stage, and crippling failures, in which case the product survives to the following stage although not as efficiently as required by design intent.

In this paper, the life cycle approach to failure has been discussed mainly from a theoretical perspective. It is hoped that the conceptual analysis presented here will elicit opinions and comments from engineers and designers such that their expert opinion will be integrated into future steps of this ongoing research.

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