TEXT MINING OF RESILIENT OBJECTS ABSORBING CHANGE AND UNCERTAINTY

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TEXT MINING OF RESILIENT OBJECTS ABSORBING CHANGE AND UNCERTAINTY

Panarotto, Massimo (1);
Giordano, Vito (2);
Chiarello, Filippo (2);
Brahma, Arindam (1);
Alonso Fernández, Inigo (1);
Fantoni, Gualtiero (2)

1: Chalmers University of Technology;
2: University of Pisa

ABSTRACT

The current ways of coping with uncertainty such as changes during product design or use have been through methods such as easy restructuring (e.g., modularity with buffer in interface definition), by overdesign and so on. The present investments on maintaining products in the economy for "as long as possible" is challenging these strategies from a cost and environmental perspective. Moreover, these strategies often lead to highly overdesigned products. An alternative strategy is to introduce features in a design, called "resilient objects", which are able to absorb such uncertainties without wasteful overdesign of other parts. By applying a 'text-mining' approach on patents, this paper has identified 5,552 candidates for such resilient objects that can be recombined and inserted in regions of the product that are likely to be most affected by current and future uncertainties. The application of resilient objects is demonstrated on a case study (a cooling system for battery electric vehicles). The case study highlights the ability of these objects to 1) significantly increase protection against uncertainties without the need for restructuring, 2) reduce the risk for overdesign and 3) dampen effects of change propagation.

Keywords: Resilient objects, Semantic data processing, Tech mining, Product architecture, Uncertainty

Contact:
Panarotto, Massimo
Chalmers University of Technology
Sweden
massimo.panarotto@chalmers.se

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1 INTRODUCTION

Many uncertainties are affecting the development of products today. Customers are posing increased demands on product functionality, and regulatory requirements are expected to increase. Also, new ground-breaking technologies (e.g., electrification and automation) are maturing and are expected to be integrated into such advanced products. At the same time, following the examples of circular economy business models, manufacturing companies are also investing in ways to maintain products in the economy for "as long as possible" (Stahel, 2016). For product developers, this means an increased need to conceive a product able to cope with uncertainties for a longer period than what happens today (Pieroni et al., 2019).

So far, much of the industrial practice has focused on designing products that cope with uncertainty through easy restructuring. For example, by leveraging the concepts of modularity (Otto et al., 2016) and increasing the ability to change modules in the platform by using standardized interfaces (Ulrich, 1995). These design approaches strive for conceiving systems with relatively low capability initially, but at the same time, allow for expansion if changes occur (De Neufville et al., 2011). While applying these approaches may have many benefits, they have several drawbacks. Given the often high rates of change expected, dealing with uncertainty through restructuring could result in modules being continuously added and altered to modify the system structure, no matter how easy the change of the module can be made. This has negative implications for both the cost efficiency of the manufacturer, as well as sustainability for society.

One alternative to avoid restructuring could be to increase the margins in the design, specifically in regions that are most likely to be affected by changes (Eckert et al., 2019; Brahma and Wynn, 2020). These margins can therefore provide usable excess if requirements for higher capacity should arise (Tackett et al., 2014; Cansler et al., 2016). This way of managing margins, although useful from a system evolvability perspective, can result in overdesign (Eckert et al., 2020; Jones et al., 2020), which also has negative implications for cost efficiency and sustainability.

This paper considers a third way to guarantee protection against uncertainty without the need for restructuring while maintaining the product as "near net shape" (Altan and Miller, 1990) as possible. This paper proposes the introduction of "resilient objects" in regions of a product that are susceptible to high risks due to change. Here, resilient objects are defined as *"any kind of physical element to be used in a system not only to absorb the effective change but also bringing back the system to its original state without the need for changing the product structure"*. Following this definition, one can observe that resilient design objects are already common in practice, such as spring-damper systems in mechanical systems. However, products are often multi-technological, which means that risks in components comprising of one type of technology may propagate to another. This paper therefore proposes a way of representing generic resilient objects and design solutions for such multi-technological systems.

Literature has already investigated such generic objects, for example by defining 'change absorbers' as objects that cause no further change whilst accommodating several changes (Jarratt et al., 2011). However, this paper looks at these objects at a deeper level of granularity. We do this by applying a 'text mining' approach (Nadeau et al., 2007), retrieving and sorting 5552 possible resilient objects from existing patents. The last part of the paper focuses on an illustrative example highlighting the use of such resilient elements of different natures during the early design of a complex system subject to high levels of uncertainty and change.

2 BACKGROUND

2.1 Approaches to absorb change and uncertainty

Conceiving a system that is protected against uncertainty is well understood in design (Thunnissen, 2005). Designers often use interventions to protect against uncertainty, either explicitly or implicitly (Crawley et al., 2004). These interventions result in the design possessing systemic properties often grouped under the term 'ilities' (e.g., changeability, flexibility, adaptability, scalability; Ross et al., 2008). In the field of engineering design, Chalupnik et al. (2013) made a classification based on the point of view that ilities provide various forms of system reliability (i.e., minimising unwanted variance in performance'). The classification is based first on the source of the uncertainty that the ‘ility’ concept protects against; system, environment or requirements. In traditional reliability literature, systems are considered reliable as they have predictable performances in stable environments and stable requirements (Chalupnik et al., 2013). However, systems often are subject to changes both in the environment and in requirements. When the environment is subject to change and the requirements remain stable, robustness and adaptability concepts can be applied. Robustness and adaptability have similar definitions in literature. When the system is also subject to changes in requirements, the concepts of versatility, resilience and flexibility can be applied. In versatility, changes in the environment are not considered (Chalupnik et al., 2013). Resilience and flexibility instead consider changes in the environment (besides changes in system and requirements). Although there are no univocal and distinct definitions of resilience and flexibility, their differences are considered to be in the means used to cope with uncertainty (Chalupnik et al., 2013). While resilience focuses on minimising the impact of uncertainty without changing the structure (passive protection; Chalupnik et al., 2013), flexibility implies uncertainty minimization through restructuring (active protection; Bordoloi et al., 1999). Resilience on the other hand, implies the ability of a system to ‘return to its original (or desired) state after being disturbed’ (Christopher and Rutherford, 2004) and the ability to ‘bounce back from adversity. Some general design principles to achieve resilience are possessing reserves to accommodate unforeseen changes (Hollnagel et al., 2008), absorbing and utilising change, recovering from perturbation (Fiksel, 2007), preventing adverse events.

Although literature has described the ways to achieve resilience, the practical means to realise resilience in a system are less characterized (i.e., which elements to be inserted and designed to increase resilience in a system). The next section highlights how ‘text mining’ can be used to identify such elements.

2.2 Text mining for functional patent analysis

Text mining is a subfield of computer science that focuses on the analysis of unstructured textual data for extracting relevant information (Gupta et al., 2009). In the last few years, several studies have applied text mining techniques for mining information from technical documents, such as patents, for instance, to help the decision-making process (Chiarello et al., 2019). Siddharth et al. (2022) provide a detailed literature review highlighting relevant papers in the intersection between text mining and engineering design. In the broad body of literature, the seminal work of Cascini and Russo (2007) analyses the TRIZ evolutionary trend structuring a patented invention as a functional diagram.

The text mining method for recognizing functions from texts is called Named Entity Recognition (NER). According to Giordano et al. (2021), there are three approaches of NER: (i) gazetteer-based method, which uses a lexicon (gazette in jargon) to map the appearance of a function in the text; (ii) rule-based method, which relies on regular expressions and morphosyntactic rules to build a knowledge base able to recognize functions in textual data; (iii) machine learning method, which build a model based on a golden set (instances of entities, i.e., functions in our case) to retrieve function from texts. Cascini and Zini (2008) use the gazetteer-based method to compare the functional trees of different patents and estimate their conceptual distance. Similarly, Liu and Huang (2018) extract functions from patents from building an effect matrix and understand the similarity among different technologies. Other authors use a rule-based approach for extracting functions from the text. Among rule-based text mining, the most used method is the Subject-Action-Object approach, where the Action-Object (AO) represents the functions of a technology (Choi et al., 2011; Yoon et al., 2013). There are few applications on machine learning-based NER for extracting functions from patents since machine learning requires a huge dataset of annotated functions, which is hard to build. For this reason, most studies rely on gazetteer or rule-based methods.

3 TEXT MINING OF RESILIENT OBJECTS ABSORBING CHANGE AND UNCERTAINTY

This section presents the methodology to collect data on resilient objects which absorb change and uncertainty from patents. Figure 1 shows the method of our paper which is composed of the following steps: (1) search and retrieve a set of patents on resilient objects absorbing change and uncertainty; (2) build the lexicons to recognize the functions of change absorber components using Named Entity Recognition (NER) techniques; (3) apply NER for collecting different resilient objects absorbing change and uncertainty and map the relationships between these objects. These methodological phases are described in detail in the next subsections.

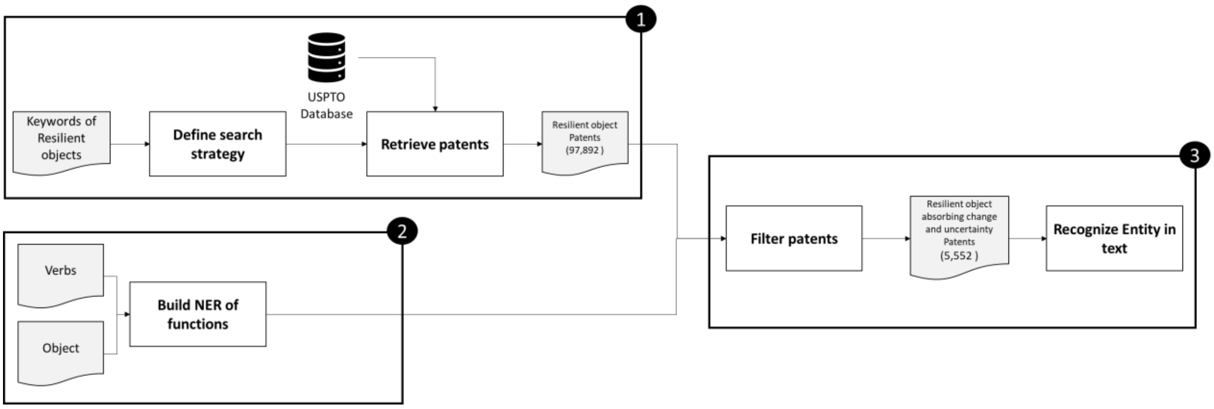

Figure 1. Flowchart of the methodology.

3.1 Retrieving patents on resilient objects

The goal of this stage is to collect patent documents related to resilient components absorbing change and uncertainty. We implemented different search strategies based on keywords for collecting patents about the topic of interest. The definition of resilient objects was used to select relevant keywords. In particular, as defined in Section 2.1, the main characteristic of resilient objects is the capability of resilience. For this reason, we collected all the patents containing the keywords related to resilience which are "*return, bounce back, rebound, recover, recuperate, go back, to original state, disturbance, adversity, unchanged structure, without modifying the structure, without changing structure, and passive protection"*. The keywords were searched in the title and abstract of patents. The patents were retrieved from the United States Patents and Trademark Office (USPTO) database, using the R package "*patentsview*"[1]. This approach was executed on November 2022 and led to the collection of 97,892 patents.

3.2 Knowledge base of component functions absorbing change and uncertainty

The approach to NER used in this article is based on rule-based methods (a structured set of regular expressions and morphosyntactic rules), to recognize in the abstracts of the patents the functions of change absorber components. This method builds a knowledge base to map mentions of entities within texts (Nadeau et al., 2007). We used well-known rules for identifying functions: functions are expressed in the text using couples Verb + Object (Fantoni et al., 2013). We relied on the knowledge base developed by Hirtz et al. (2002), selecting only functions (and consequently verbs and objects) that referred to the absorption of a change or uncertainty. These functions are analysed in the work of Fernández et al. (2022) and listed in Table 1.

Table 1. List of verbs and objects used for the NER system

Element	**Keywords**
Verb	accommodate, adjust, attenuate, clear, contain, dampen, demodulate, disable, enclose, inhibit, insulate, invert, modify, modulate, normalize, prevent, protect, recover, rectify, reset, resist, scale, shield, turn-off, vary
Object	analog signal, angular velocity, auditory signal, biological energy, change, chemical affinity, chemical energy, chemical reaction rate, decay rate, discrete signal, electric current, electric energy, electromagnetic energy, electromotive force, force, gas, gas gas, heat rate, human energy, human force, human part, human velocity, hydraulic energy, hydraulic pressure, linear velocity, liquid, liquid gas, liquid liquid, magnetic energy, magnetic flux rate, magnetomotive force, mass flow, mechanical energy, object, olfactory signal, optical energy, optical intensity, optical velocity, particulate, pneumatic pressure, radioactive intensity, rotational energy, solar energy, solar intensity, solar velocity, solid, solid gas, solid liquid, solid liquid gas, solid solid, tactile signal, taste signal, temperature, thermal energy, torque, translational energy, visual signal, volumetric flow

[1] https://cran.r-project.org/web/packages/patentsview/index.html (opened in December 2022)

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3.3 Named entity recognition

The approach to NER used in this article is based on a rule-based approach that maps functions of the previously defined knowledge base within texts. The NER method identified the functions in each of the abstracts. Then the occurrences of all these functions were identified in the patent corpus. The NER system was used to filter relevant patents for our study, i.e., only the patent containing at least one function of the knowledge base (in the title or abstract) was selected. Out of our original corpus, 5,552 such patents were selected for the analysis.

In Figure 2, we can observe the heatmap of the occurrences in patents of each function (a pair of a verb and an object) resulting from our analysis. The verbs that were related to change absorber components are shown on the x-axis of Figure 2, while the y-axis represents the objects extracted from the NER system.

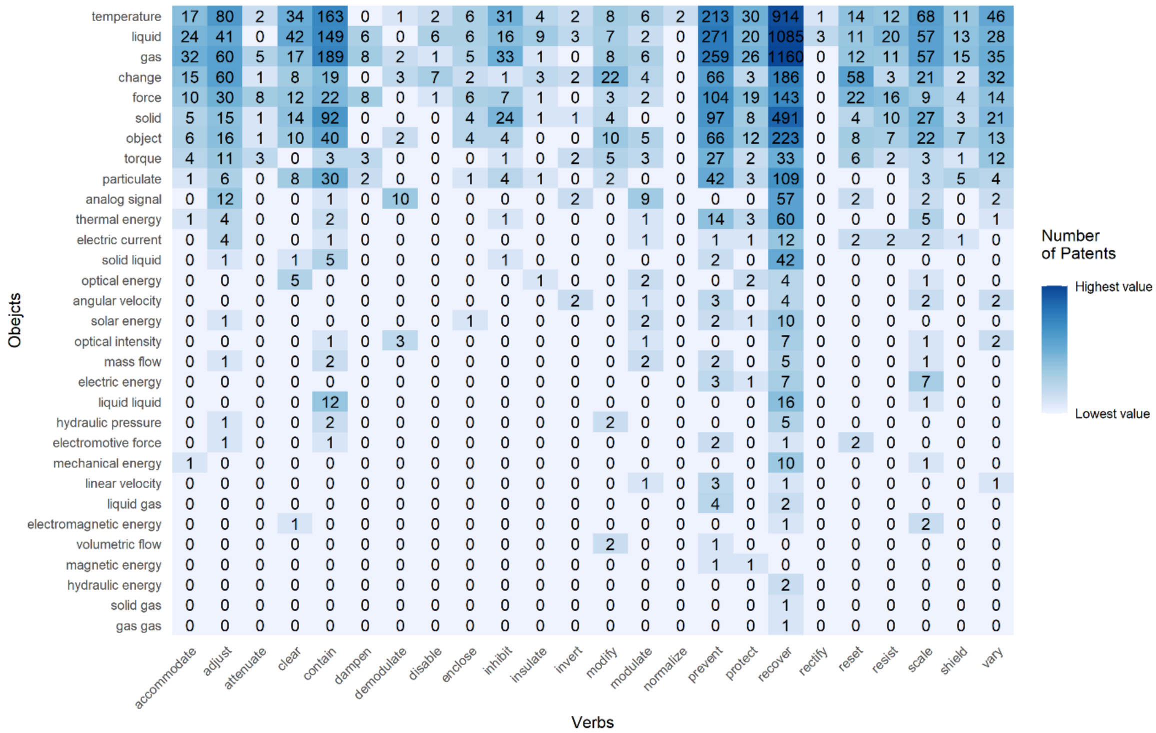

Figure 2. Heatmap of patents number for each function. The intersections with large numbers of patents are shown in darker blue, while small numbers are shown in white

The heatmap provides evidence of the cardinality of an intersection by using a colour scale: the intersections with large numbers of patents are shown in darker blue, while small numbers are shown in white. In addition, the heatmap makes the gaps and blind spots explicit, identifying the empty regions of the matrices. In each cell, we also report the number of patents mentioning a given function. Moreover, we show in Figure 2, all objects of Table 1 which have at least one patent.

We can observe from Figure 2 that objects such as *temperature*, *liquid*, *gas*, *change*, and *force* have a high number of patents for most verbs. The verb *recover* has the highest number of patents. The most recurrent functions of resilient objects absorbing change and uncertainty are '*recover gas'* (1,160 patents) and '*recover liquid'* (1,085 patents).

4 APPLICATION OF RESILIENT OBJECTS TO THE DESIGN OF A COOLING SYSTEM FOR A BATTERY ELECTRIC VEHICLE

This section illustrates how the notion of resilient objects can be applied during the early design of a complex system. The example chosen is the cooling system for an electric powertrain of a Battery Electric Vehicle (BEV). Figure 3 shows the 11 components and the Design Structure Matrix (DSM) of the cooling circuit (adapted from Yamagishi and Ishikura, 2018).

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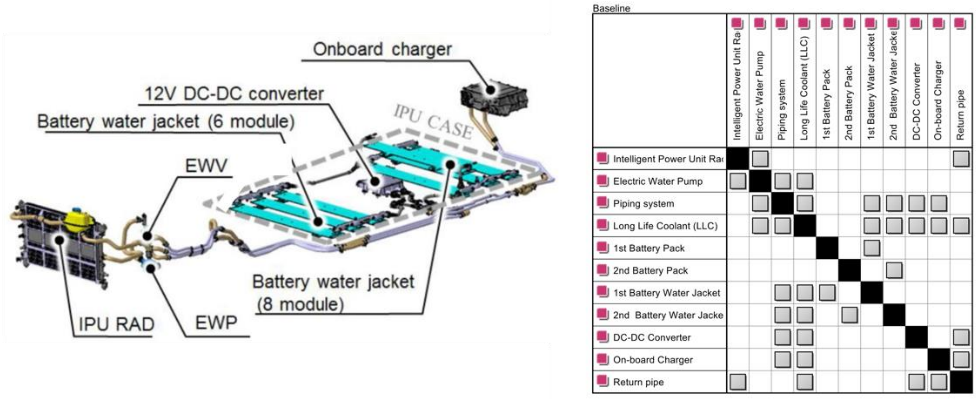

Figure 3. Components and DSM of a cooling circuit in the electric powertrain for a battery electric vehicle (adapted from Yamagishi and Ishikura, 2018). EWP = Electric Water Pump, RAD = Radiator, EWV = Electric Water Valve, IPU = Intelligent Power Unit.

The components cooled by the system are the two battery packs, a DC-DC converter, and the onboard charger. The system uses both an electric water pump (EWP) and a radiator (RAD) dedicated exclusively to the electric powertrain, positioned at the front of the vehicle. After the battery is cooled by the circulation of long-life coolant (LLC) through water jackets. The circulation is made possible by an electric water pump (EWP), and a piping system. After cooling, the coolant returns to the radiation through a return pipe. This system is considered to be the 'baseline' system against which the effects of changes are going to be analysed.

4.1 Absorbing changes: overdesign vs. using resilient objects

Figure 4 shows the results of the Change Propagation Method (CPM; Clarkson et al., 2004) applied to three different alternatives of the cooling system, using the Cambridge Advanced Modeller (CAM) software. CPM is chosen here for its ability to quickly initiate change in a system and to evaluate the impact of change propagating in the system (although other methods could be used). Following industrial practice (Yamagishi and Ishikura, 2018), this example considers a change made in the two battery packs and the onboard charger. These three elements are changed in the baseline system (Figure 4-a) due to the need of increasing the range while reducing the charging time of the vehicle. This leads to an increased capacity of the battery packs, while the onboard charger increases in terms of power. To analyse the impact made by these changes at an early stage, the CPM method is used. For simplicity, the likelihood (L) and impact (I) values have been set high (i.e., both 0.8) for the battery packs and the onboard charger. All the other L-I interactions have been set to 0.5 and propagated 3 times (for third-order effects) through the system.

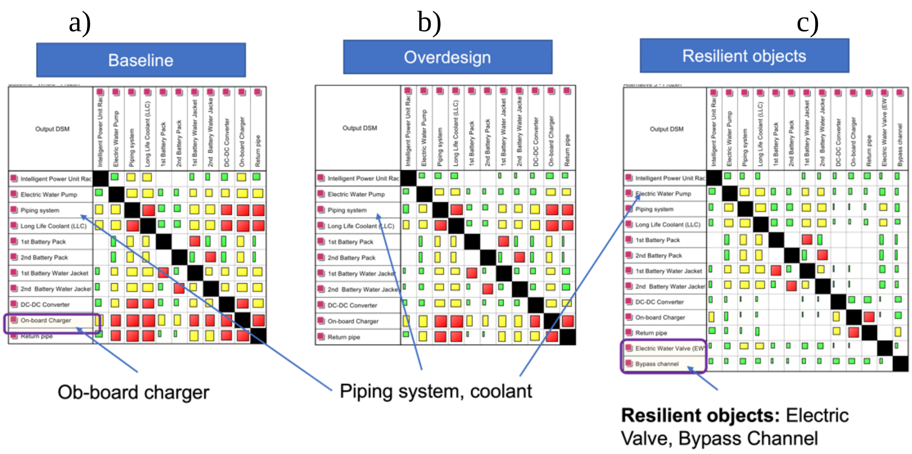

Figure 4. Impact of change propagation on a) baseline b) overdesigned system c) baseline design with resilient objects.

As it can be noticed from Figure 4, the baseline system results are highly perturbated by these changes. This is because of the very tight connections between the battery packs and the onboard

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charger, through the piping system, the coolant and the return pipe. This resonates well with practice. In fact, the battery is the main source of heat generation during vehicle operation, but when the vehicle is being charged, the onboard charger is the main source of heat generation. If all the components are cooled using the same coolant channel, the heat generated by the charger during charging would cause the battery temperature to increase, resulting in the degradation of the battery (Yamagishi and Ishikura, 2018).

One way to prevent this is to overdesign the piping system, the amount of coolant and the return pipe (Figure 4- b). In CPM, this has been simulated by setting low L-I values for the interactions provided by these components at 0.4. This strategy is to dampen the propagation chain in the system but at a higher cost associated with the overdesign. Also, since the onboard charger and the batteries are still connected through the cooling channel, the system is not resilient towards a further increase in the capacity of the battery packs and the onboard charger.

Another way to prevent the flow of heated coolant from the on-board charger to the battery is to remove this interaction by inserting one or more 'resilient objects' (Figure 4-c). In this example, this is done through the insertion of an Electric Water Valve (EWV) and a bypass channel. In CPM, this was simulated by setting the L-I values of these interactions to 0.4, while maintaining all the other values at 0.5 (to consider the baseline system that is not "overdesigned"). The results show how the overall propagation of change is reduced, through the insertion of these two resilient objects. Also, it shows how the system is resilient towards new changes in the battery packs and the on-board charger since the heat generation problem is prevented through the elimination of the interaction. This again resonates with the design practice. The system developed by Yamagishi and Ishikura (2018) employs a bypass water channel and an EWV that switches coolant circuits when the temperature of the coolant is higher than the temperature of the battery. During charging, a high level of heat is generated by the onboard charger, increasing the temperature of the coolant. Increases in battery temperature are therefore avoided by sending the coolant through the bypass circuit when the coolant temperature is higher than the battery temperature. Looking at the Text mining results of Figure 2, a valve with a bypass channel is present in many patents aiming at "preventing material" (for example; Freen et al., 1997; Andel and Walsh, 1999).

This example has shown the application of resilient objects matched with the industrial practice, yet it is appealing to apply the Text mining results to design resilient objects that consider more failure modes than only heat generation. The next section will describe this in more detail.

4.2 Applying the text mining results to design 'super-resilient' objects

The main motivation to systematically apply the Text mining results to the design of resilient objects is due to the increased interest by companies to maintain products in the economy for "as long as possible" (Stahel, 2016). This could mean a product alone, or a product platform with an extended life which may encounter many uncertainties over time. One example of these uncertainties could be future technology integrations, that may cause unexpected adverse events and failure modes. Figure 5 shows an example of how to apply the Text mining approach to design "super-resilient" objects that absorb many future adverse events and failure modes (that could be unknown to the firm).

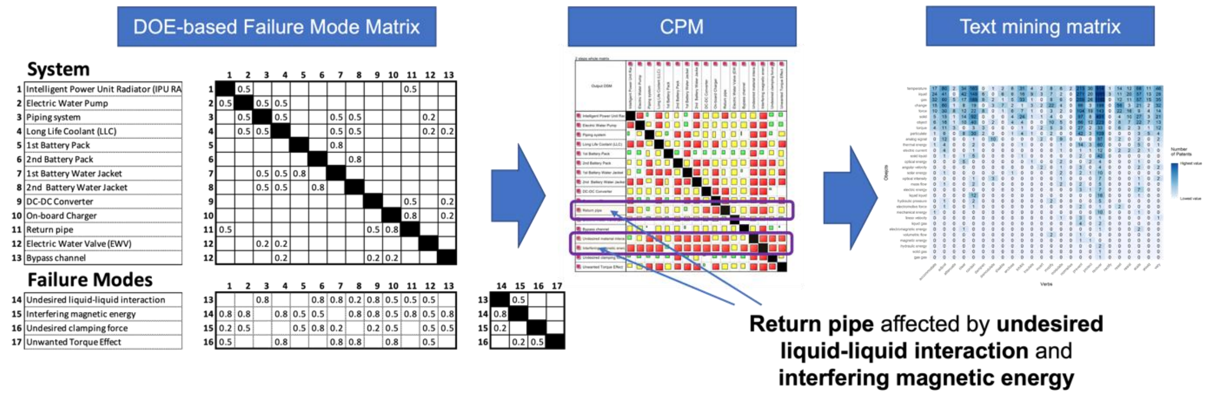

Figure 5. General process for designing super-absorbent resilient objects

The process starts by creating a matrix of possible "failure modes" alongside the DSM of the system. These failure modes represent possible technical problems connected with the introduction of future

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technologies in the system. In the example of the cooling system, 4 failure modes were considered: *undesired liquid-liquid interaction*, *interfering magnetic energy*, *undesired clamping force*, and *unwanted torque effect*. In an ideal scenario, the interaction between the failure modes and the elements of the system (as well as interactions among the failure modes) are introduced and varied according to a design of experiments technique (following approaches already adopted in other research, e.g., Fahmy et al., 2012). These interactions are the L-I values representing the likelihood and the impact of these future failure modes. The application of CPM then makes it possible to understand the most critical components from a change perspective, that are critical for the resilience of the system. Interestingly, for the example case being discussed, the CPM analysis shows a relatively low risk for the Electric Water Valve (EWV) and a bypass channel (although they present high L-I values). This means that these two components are already resilient, and any changes in them do not propagate through the system. Instead, other components seem critical to certain failure modes, in particular the coolant, the on-board charger and the return pipe. The example focuses only on the return pipe, primarily for simplicity and also because absorbing change in the return pipe will positively affect the coolant as well. From the analysis, it can be noticed that the two most influential failure modes on the return pipe are *undesired material interaction* and *interfering magnetic energy*. These failure modes could come, for example, from a new and undesired interaction with a new technology that will be placed near to the return pipe in the future. Therefore, the return pipe should be redesigned to contain elements that absorb these possible future failure modes (due to technology integration).

At this point, the designer investigates the results of the text mining approach (Figure 2) to get inspiration about potential design solutions which may help to absorb material interaction and magnetic energy, creating a "super-resilient" object for the return pipe. Figure 6 shows an example of such an object.

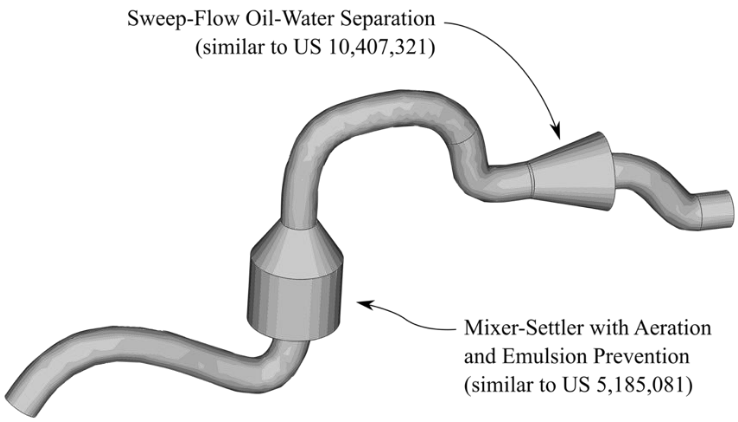

Figure 6. CAD drawing of the return pipe as "super-absorbent", preventing liquid-liquid interaction and shielding magnetic energy. The patent solutions visualized are only demonstrative

Reading the "liquid-liquid" row of the matrix shown in Figure 2, the designer can potentially identify 29 possible solutions for "absorbing" liquid-liquid interaction. The same is done for "magnetic energy", where only 2 possible solutions for absorbing magnetic energy are identified. These solutions then become input to an engineering design process, with the purpose of designing a "super absorbent" object for the return pipe, the primary requirement of which being able to prevent liquid-liquid interactions and providing shielding from magnetic energy. For preventing liquid-liquid interaction, the sweep-flow oil-water separation mechanism patented by Miller and Bell (2019) is used as inspiration. For shielding magnetic energy, the mixer-settler mechanism patented by (Nyman et al., 1993) is used as an example.

5 DISCUSSION AND CONCLUSION

The "super-resilient" return pipe example has demonstrated how "resilient objects" can be used as an effective alternative to cope with changes in an engineering system. So far, much of the literature has focused on coping with design changes through easy restructuring (e.g., Otto et al., 2016) or overdesign (Brahma and Wynn, 2020) with increased design margins. Designing super-resilient

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objects (augmented by the text-mining approach) allows to combine discrete and non-parametric design solutions (i.e., working at a higher system level than those provided in previous research) to absorb future changes without the need for restructuring. This ability is timely due to the increased industrial interest in designing systems able to cope with uncertainty without increasing cost and environmental impact. However, there is a need to consider a key trade-off between the ability of resilient objects to avoid restructuring (therefore consuming less resources) against their cost and environmental impact. In fact, the use of a resilient object could in some cases overcome its advantage in terms of resource efficiency (compared to restructuring and overdesign) due to the cost and environmental impact of the resilient objects themselves. Further, there is a possibility that the introduction of a resilient object may change the propagation path completely, shifting the point of failure to a previously resilient part in the design, which may be undesirable.

Future work will focus on how to identify the most sensitive components from a resilience perspective. The CPM analysis used in this paper provides a first-order estimation of such impact, yet more refined interface knowledge is needed to provide a sounder decision basis.

Also, the ways in which the 5552 possible resilient objects provide absorption of failure modes have not been characterized. Future work will analyse deeper the patents to find patterns of resilient design, much like what is done in TRIZ (Cascini and Russo, 2007).

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