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Procedia CIRP 98 (2021) 121–126

www.elsevier.com/locate/procedia

28th CIRP Conference on Life Cycle Engineering

Complexity of self-engineering systems across the life cycle – Biological and engineering systems

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Abstract

A self-engineering (SE) system is an ability designed and built into a system which allows it to respond to functionality lost automatically and restore it fully or partially to maintain its availability. Examples include self-healing, self-repair, self-reconfiguring, built-in redundancy and self-adapting systems. SE systems aim to increase products useful life and extend its use phase. In previous research a complexity framework for identifying complexity of SE system was outlined; this paper builds on this research and investigates the impact complexity on all stages of the lifecycle of SE systems. The key stages of the lifecycle of SE systems is evaluated to identify additional complexity factors which should be considered. With the increase in the development of SE technologies, it is important to understand the lifecycle of these systems and the effect of complexity.

Keywords: Self-enigneering; self-repair; lifecycle; self-healing; sustaibability

1. Introduction

Extension to product life is a key aim for designers; regular maintenance, repair and overhaul (MRO) services are still required to prolong products life. Future products and systems may be inaccessible to humans or expensive to reach regularly; for these systems, more ambitious approaches are needed such as *Self-engineering* (SE) systems. A SE system is defined in Roy and Brooks [1] as "*An ability designed and built into a system to independently identify loss or potential loss of function, and then automatically restore the functionality fully or partially to maintain its availability and improve resilience*".

There are four key characteristics of a SE system which have been identified. Firstly, it must restore or partially restore lost function or capacity, which has occurred or will occur. Secondly, it must be built into the system, not added later when required. Thirdly, the aim should be to avoid/reduce maintenance, prolong life and/or increase the system resilience and robustness. Lastly, there must be no human/user intervention; any process, response and behavior should be automatic. SE systems can be divided into two categories, those with control and those without [1].

This paper presents a literature review on lifecycle implications of SE systems. There is a lack of research in this area and therefore the paper also uses expert view and analogy with similar engineering systems. Ensuring the sustainability of SE systems will be key to their future success. SE systems should ideally be able to offer life extension and help maintain functionality of products without compromising the needs of future generations.

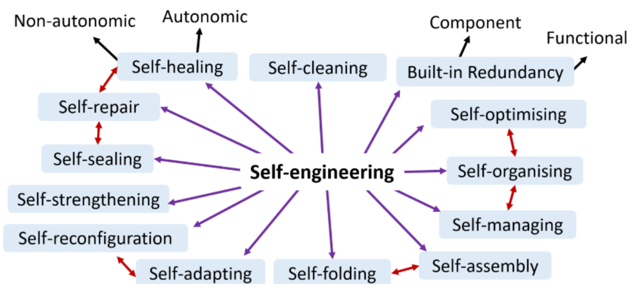

Fig. 1 – Diagram of SE key SE terms.

10.1016/j.procir.2021.01.016

1.1. Current Self-engineering Systems

There are many examples of these systems already used in engineering, a diagram of different SE terms is shown in Fig. 1. Self-healing materials have been extensively researched; examples of early work includes self-sealing concrete cracks, self-healing microcapsule polymer composites [2] and vascular self-healing composites [3]. These systems focus on releasing a liquid polymer which hardens to seal cracks and prevent growth. Other self-healing materials focus on chemical bonding which can be repaired by the addition of a stimulus such as heat for Diels-Alder polymers [4].

Self-repair of electronics is a well-advanced area with many electronic systems now including built-in self-repair (BISR) and built-in self-test (BIST); however, this self-repair is a self-reconfiguration of the system to utilize redundant components. For example, RAM devices have been created with BISR and BIST [5]; faulty memory cells are identified, and a system reconfiguration performed to ensure they are not utilized and spare cells are used instead. In robotics, many swarm systems have been designed to self-assemble into a set shape, assemble new robots and even self-repair a function when robots are removed [6]. Other robotic systems have focused on making robots which can self-adapt like animals to a missing or damaged limb [7].

Brooks and Roy [8] presented the validation of a SE complexity framework created by evaluating biological and engineering SE systems. Biology is a key area of inspiration for self-engineering; examples of SE systems already inspired by biology include blood vessels to deliver healing agent, self-sealing pneumatic structures and hierarchical organization structures for self-reconfiguration.

1.2. Self-engineering Complexity

The complexity framework presented by Brooks and Roy [8] outlines three factors identified as contributing to the complexity of the SE system in biology and engineering.

Redundancy: The more redundancy in a system, the more complex it becomes. Redundancy can be functional redundancy as defined in [9].

Repeatability: Not the scientific repeatability of the response, but how many times a system can respond. Many self-engineering systems are only designed to respond once to a loss of function, as the quantity of times response can occur increases, so does the complexity.

Control (or self-control): The lowest level of complexity is SE systems without control, such as autonomous self-healing materials; these systems react to outside stimulus or damage without a control or conscious decision process. A more complex system uses a control system to manage all aspects of the SE system. The highest level of complexity is when multiple control systems or sub-systems are interacting, creating unpredictable or emergent behavior.

2. Lifecycle of self-engineering systems

Self-healing materials are the most advanced area of SE engineering and where the majority of research on lifecycle engineering has focused. Most papers on self-healing and SE systems do not report details on the disposal or recyclability of the materials. More recently, authors experimenting with new self-healing hydrogels [10], Diels-Alder polymers [4] and liquid metals [11], have include details on the recyclability of their materials.

Akrivos et al. [12] evaluated metrics used for self-healing materials and how metrics could be improved for a circular economy. Current metrics were found to be limited to one parameter (such as compressive strength, stiffness, thermal conduction) and evaluating how it is maintained after healing. Links were drawn between self-healing metrics and possible comparable circular economy metrics. Cseke et al. [13] also evaluated self-healing materials with regard to lifecycle engineering. A Life Cycle Healing Efficiency metric was defined to indicate the loss of functionality occurring each healing cycle. This could be used to compare potential self-healing materials to identify ones which would maintain functionality above a set level longest. This work could be adapted for SE systems. However, it only considers one material function and not multiple functions.

Extending system life with SE systems will often come at the cost of energy or material inputs to drive the process or changes to the system design. The impact of this on the whole lifecycle is not considered in current research on SE systems. This paper aims to begin to address this area.

3. Engineering systems.

Three SE systems have been selected and the impact of the added SE system has been evaluated at each lifecycle stage: material extraction/processing, manufacturing, use, and recycling and disposal (as outlined in [14]). Case studies were selected because they all utilize different SE strategies they were also all in different engineering disciplines.

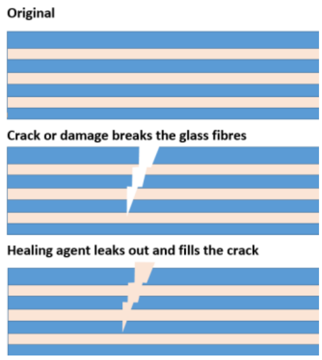

Fig. 2 – Diagram of self-healing vascular material healing a crack. Reported in [3]. Healing agent in light orange; solid composite in blue.

3.1. Case study 1: Self-healing vascular material

The self-healing material evaluated here is a composite material made up of thermosetting plastic and hollow glass fibers containing a liquid healing agent (reported in [3] and shown in Fig. 2), Table 1 shows a summary of the review.

The lifecycle of composite materials and parts has been evaluated by previous authors and drawn on in this evaluation due to the lack of studies evaluating self-healing materials lifecycle. In terms of material extraction, most polymer and polymer composites use materials derived from crude oil, a finite resource with a costly environmental footprint. Total energy used in processing and manufacturing composites and steel has been shown to be similar, but aluminium is often higher [15]. The addition of hollow liquid filled tubes increases the complexity of composite manufacturing and would likely increase the length and cost of production, though this is undefined and untested in current research.

Table 1 – The impact on different stages of the lifecycle of adding a self-healing vascular property compared to a regular composite.

Lifecycle stage	Impact of adding SE
Material Extraction and processing	More polymer material needed to account for reduced strength from adding hollow fibres rather than solid.
Manufacturing	The addition of hollow fibres and liquid agent increases complexity of manufacturing processes.
Use	Life is extended because micro-cracks are repaired before they grow, maintaining material strength. Material quantity could increase due to reduced strength or decrease because of lower design margins needed. No additional energy required for healing.
Recycling or disposal	Added healing agent and hollow tubes make the composite harder to recycle.

Benefits of composites are seen in energy savings during the use stages, where the high strength to weight ratio enables less fuel use when composites are used in vehicles [15]. The added self-healing capability will increase composite weight but not strength reducing this benefit; however, use of self-healing may allow for lower design margins and lower thickness composites keeping the total weight similar.

The main benefit of self-healing will be in the product life extension without the need for maintenance. Damage which may have required the part to be removed from service previously could be endured. The extension of life will depend on the materials ability to return functionality (such as strength or stiffness) to the required level repeatedly; this ability degrades after each healing cycle. Data on repeated healing cycles is often not reported, making it difficult to predict the exact life extension from self-healing.

Composite disposal is still significantly costlier than metals or single plastics due to the difficulty of separating and reusing the material components. Composite recycling techniques and market demand for the recycled material are growing [16]; however, material properties are not maintained during recycling. The addition of a further healing agent complicates the material separation and recycling further. The exact impact of recycling is unknown because no evaluations have been carried out.

3.2. Case study 2: Self-adapting robot

Mechatronic systems are becoming more prevalent in our everyday environments. A self-adapting robot (from. [7] shown in Fig. 3) which adapts to a missing or damaged limb is evaluated; a summary is shown in Table 2. The self-adaption process is coordinated by a central computer which registers the lost movement and models and implements a response.

The raw materials of robotics include metals and plastics which make up complex electronic parts. The lifecycle of electric parts (and the e-waste produced) has been an extensive area of study with many issues still to be solved. The self-adapting mechanism on the robot is reliant on the presence of redundant limbs which require more resources and energy to carry and produce; however, these may already be present on a robot to provide stability and robustness. Extra processing and memory capacity could be required to store and run the self-adaptation process efficiently, increasing the resources required. Modern robots often have this high processing power built-in because it is cheap and easily available.

Table 2 - The impact on different stages of the lifecycle of adding self-adaption to a multiple legged walking robot.

Lifecycle stages	Impact of adding SE
Material Extraction and processing	Extra materials and processing needed for redundant limbs.
Manufacturing	Extra limbs need to be assembled and added
Use	The self-adaption mechanism takes time and power to run, but it can maintain the robot despite damage. Extending its life span.
Recycling or disposal	Extra limbs mean more parts and material to recycle or dispose of.

During the use stage, there will be little difference in the operation unless numerous redundant legs are added. The self-adapting system will provide significant life extension because it enables the robot to be operated beyond faults that would otherwise incapacitate it. The addition of the self-adapting system will not affect the disposal significantly because it is software-based; however, the redundant limbs used will increase the number of parts and material to dispose of.

The base self-adapting system itself will have a net positive effect on the robot's lifecycle, extending its useful life. However, the redundant limbs and extra processing power needed for a fast repair will not have a positive impact. A designer would have to balance the cost of carrying, producing and disposing of these redundant components against the resilience required.

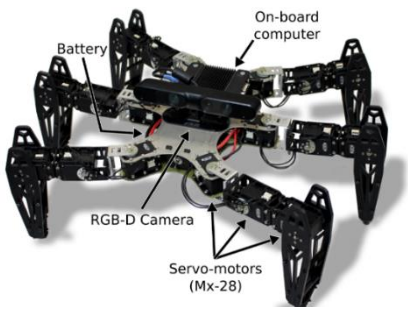

Fig. 3 – Picture of self-adapting hexapod robot, original research in [7], and image from [17], ©Antoine Cully / Pierre and Marie Curie University. Licensed under CC BY [18].

3.3. Case study 3: Self-reconfiguring RAM

A BISR, or more accurately self-reconfiguring, RAM requires spare memory cells to be available to replace damaged ones and additional circuitry to manage the reconfiguration [5]; Fig. 4 shows the basic repair process. A summary of the evaluation is shown in Table 3. The main benefit of the BISR is for a RAM on an integrated circuit (IC). Degradation of one part could lead to the whole IC being replaced, BISR RAMs can sense and take action to preserve the RAM and the circuit.

Table 3 - The impact on the different stages of the lifecycle of adding self-reconfiguration (BISR) to an IC RAM device.

Lifecycle stage	Impact of adding SE
Material Extraction and processing	Extra materials needed for spare memory cells and extra circuitry.
Manufacturing	Energy needed to manufactures spare memory cells and circuitry.
Use	The self-reconfiguration extends the life of the RAM and keeps it functioning accurately despite damage or degradation of cells.
Recycling or disposal	Extra cells and circuitry to be recycled and materials separated

The additional memory cells and circuitry require additional raw materials and resources. However, the spare cells are often only a small fraction of the total cells. RAM recycling is higher priority in e-waste because of the high-value metals used. Current recycling processes focus on metal component extraction often neglecting toxic plastics components [19]. Processes often require harsh chemicals or high energy inputs with little material recovered. Recycling processes are often designed to process multiple RAMs at once and would, therefore not be significantly affected with the addition of extra cells or circuitry.

Obsolescence of electronic parts (such as RAM or IC) is a significant factor impacting their life expectancy. Products may be removed from service long before they have degraded [20]. A self-repairing RAM would be able to sustain performance for longer and avoid using faulty cells; however, it may become obsolete long before the full benefits of the self-repair are realized. If the RAMs are reused in other application rather than disposed of, then the BISR system will become more useful. Also, the BISR ensures any faulty cells added in manufacturing do not stop the RAM operating. Overall the addition of the BISR RAM system required relatively little extra cost compared to a regular RAM and offers useful life extension.

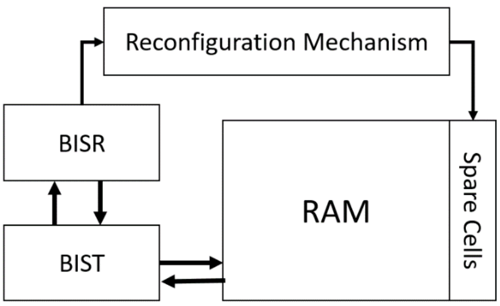

Fig. 4 - Diagram of a basic repair process BISR and BIST RAM system. Replicated from information in [6].

4. Complexity and lifecycle

4.1. Repeatability and lifecycle

Increases in the number of times a SE system can return functionality will increases the life of the system. Some systems are more reliant of this than others; for example, the self-adapting robot (Section 3.2) can only keep operating because of the self-adaptation while the BISR RAM (section 3.3.) could keep operating without the self-reconfiguration with reduced performance.

4.2. Redundancy and lifecycle

From evaluating the three SE systems above it is apparent that the addition of redundancy causes an increase in the raw materials needed, energy for manufacturing, and extra recycling of redundant parts. However, the examples evaluated predominantly consider *component* redundancy, not *functional* redundancy [9]. Functional redundancy aims to have existing components that can be reconfigured to perform other functions if needed. If existing components which are already required in the system are used, the SE system would not use extra raw materials or resources for manufacturing and recycling. For example a self-reconfiguring wind turbine could utilize one motor in the pitch and one in the yaw system (a design currently used), but include internal self-reconfiguration to utilize one motor for both functions when a motor is damaged; however, performance would likely be reduced and the reconfiguration mechanism could use extra resources.

4.3. Self-control and lifecycle

The control used in SE systems varies greatly; the system level where control is focused can change the impact self-control has on the lifecycle. For example, many material self-healing methods are reactive and are triggered by damage itself without any control; these processes are dependent on the original structure and need extra care in manufacturing [21] and recycling. However, many self-adaption and self-reconfiguring procedures are applied at a system level and can be implemented as software or control system changes. These changes do not negatively affect the lifecycle of the system and can extend the useful life.

4.4. Other complexity factors

From evaluating the SE systems' lifecycles, three other complexity factors were identified:

Resources or energy driving SE – The response of a SE system needs to be considered in more detail. The material or energy used can impact the quantity of remaining responses available; especially if the resources used have to be included and cannot be replenished like microcapsules [21].

Time for the response – The time available or taken for a response to occur will impact the complexity of the response, this has been noted in previous authors work [8] [12]. A required fast response leaves less time for planning, modelling and verification which ensure the quality of the response. It is easier to make fast responses simpler and predictable to account for this. The context in which a response must take place will affect its complexity and therefore, also lifecycle.

Complexity of operation environment – The environment a system operated is can limit its SE response. For example, some self-healing materials are dependent on certain temperatures to heal [22]. Similarly, many self-adapting or self-assembling robotic systems have only been tested on flat surfaces [7], not rough or undulating surface which will alter the speed and complexity of their movement.

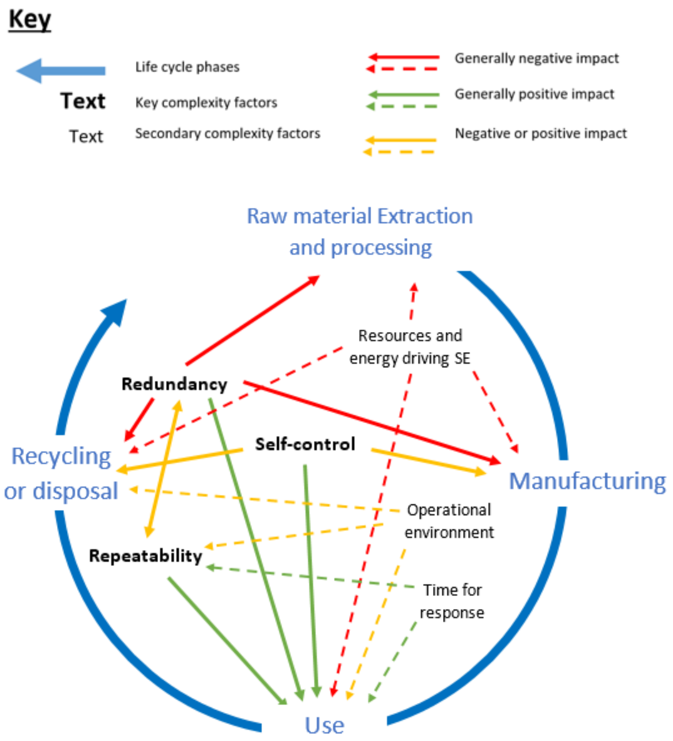

Fig.5 – Diagram showing complexity factor and the lifecycle stages they impact. Increasing the complexity (or quantity for some factors) can negatively or positively impact the lifecycle stages.

5. Biological solutions

Biomimicry and bioinspired design have been a key feature of engineering. Five areas for possible future research either inspire by or utilizing biology which could improve SE sustainability have been identified. Table 4 summarizes the lifecycle phases which could benefit from each research area.

1. *Power SE systems with clean source* – Generally, biological systems run on renewable materials, such as sunlight, water or CO^2 in plants ([23] page 74). SE powered by clean sources would reduce the environmental impact in the use phase.
2. *Energy-efficient structures* – A common bioinspired solution is energy reducing structure, examples include the Kingfisher inspired noise-reducing nose of the Shinkansen 500 bullet train in Japan. Energy-efficient structures could help reduce resource use in the use phase.
3. *Passive SE mechanisms* – These are mechanisms found in nature which require no actuation, sensing or active control. They can be difficult to replicate but use no extra energy inputs during the use phase, often the response is purely mechanical based. Examples of passive SE mechanism include self-sealing plants with latex [24] and self-reconfiguring symmetry of jellyfish tentacles [25].
4. *Clean or reusable outputs* – Biological systems output biodegradable or recyclable materials [23]. In some cases, such as the Hermit crab, shells discarded are reused preventing energy used in the use phase to produce new materials and reducing the material disposal. SE system could reuse parts from non-critical or broken systems.
5. *Utilizing biology directly* – This can help make a SE system sustainable by using renewable resources in the lifecycle and biodegradable outputs produced Parts could be grown using renewable sources such as light, food and water rather than produced using energy-intensive machines. Examples include, robots that are built with biology parts (bio-bots) to create self-healing actuators or sensors [26], self-sealing concretes developed using embedded bacteria [27], and proteins from squid replicated to create a self-healing coatings for clothing [28].

Table 4 – Identifies lifecycle phases of SE systems which would benefit from each research area outlined in section 5.

Research area number	1	2	3	4	5
Material extraction and processing	-	-	-	-	X
Manufacturing	-	-	-	-	X
Use	X	X	X	X	-
Recycling or disposal	-	-	-	X	X

6. Discussion and conclusions

SE systems offer an excellent way to extend the useful life of systems and maintain key functions. Currently, the only work investigating the lifecycle of these systems has focused on self-healing materials. Further evaluation of the extra raw material, manufacturing, and the disposal of SE systems is needed.

From evaluating complexity factors and the impact across the lifecycle of a system, it was apparent that redundancy was often linked to the number of times a system could respond (repeatability). Increasing redundancy often increased useful life but increased resources or energy needed across all stages of the lifecycle. Where a high level of redundancy is required for a SE system, the benefits in the use stage will have to be balanced against the cost to other lifecycle stages. The impact of self-control used varied depending on the method. Three other secondary complexity factors were also identified from the evaluation of the three SE systems: 1) resources or energy driving SE, 2) time for response, and 3) operation environment; these, along with the key factors are displayed on Fig. 5. The small number of systems evaluated limits the applicability of the findings, further evaluation of more SE systems and interviews with experts (as used in [8]) could be utilized to improve the validity and ensure a comprehensive and effective framework.

Biology has already inspired many SE system and can still provide many sources of inspiration. Four ways biology could inspire more sustainable SE systems are identified, though more may exist. Utilizing biology directly in SE systems can make biodegradable systems which are long-lasting though further work on the manufacturing processes is required.

Future work could focus on the balance between life extension and redundancy needed to achieve it. Another area of future investigation could be the change in SE systems over time and the impact on the lifecycle. SE systems could degrade and performance be reduced if left idle for a long time, reducing the life extension or possibly even making it harder to recycle. A final area of attention is stopping the SE system; at some point a SE response in no longer effective or needed, it may even cause damage by continuing. This point may be where a function can no longer be maintained above a set point; identifying when this point has been reached is the difficult step. Unnecessary SE responses will waste resources and energy and should be avoided to improve the sustainability of the system.

Most SE research focuses on presenting designs of new SE system. However, more research needs to focus on ensuring materials are sourced, manufactured and disposed of sustainably. New tools should assist with quantifying the life extension provided by different SE systems, to help facilitate effective comparison of designs

Acknowledgements

The authors acknowledge the support of the Engineering and Physical Research Council (EPSRC) Platform Grant - Through-life performance: From science to instrumentation (grant number EP/P027121/1).

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