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A systematic study of biological SE systems from complexity and design perspectives

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Previous research has presented the concept of self-engineering (SE) systems that aim to identify and preserve system functions autonomously. Examples of self-engineering responses include self-healing, self-repair, self-adapting and self-reconfiguration. Biology already utilises many of these responses to repair and survive, greater understanding of complexity in these biological systems could improve future bioinspired designs. This paper provides a novel systematic evaluation of the complexity of SE biological systems. Eight biological self-engineering systems identified are evaluated using Axiomatic design and complexity. The key functional requirements and design parameters for each biological system are identified. Design matrices were used to highlight different types of complexity. A further evaluation of eight SE biological systems is performed using the SE complexity theory; nine experts and 23 students used the complexity theory to complete a ranking exercise. The results of the ranking were analysed and compared, with a final normalised mean plotted for each factor and biological system. From the analysis of both studies, proposed design rules are presented to help designers handle complexity while creating new self-engineering systems inspired by biology.

Keywords: Self-healing; Self-repair; Self-engineering; Bioinspired; Design

1. Introduction

1.1. Introduction

Engineered systems rely on maintenance, repair and overhaul (MRO) strategies to prolong their useful life. In safety-critical and hard-to-reach systems, MRO can often not wait for a human technician or operator to take action; these systems and many others could benefit from implementing self-engineering (SE) systems. A SE system is defined as: *An ability designed and built into a system to independently identify any loss or potential loss of function, and then automatically restore the functionality fully or partially to maintain its availability and improve system resilience* (Brooks and Roy 2021). The four key characteristics of a SE system are: 1) it must have the ability to restore or partially restore lost function or capacity, which has occurred or will occur; 2) it must be built into the system, not added later when required; 3) the aim should be to avoid/reduce maintenance, prolong life and/or increase the system resilience and robustness; 4) there must be no human/user intervention, any process, response and behaviour should be automatic.

Previous SE research has focused on reviewing engineered SE systems (Brooks and Roy 2021). An earlier review noted that biology was a potential source of inspiration for SE (Roy and Brooks 2020); however, this has not been extensively researched. Many existing SE systems are inspired by biology, such a vascular self-healing materials (Norris et al. 2011), robotic self-adaptations (Cully et al. 2015) and self-sealing materials (Bauer, Nellesen, and Speck 2010). However, biological systems are very complex and designers need to understand where complexity is focused to enable effective designs. As the complexity of a system increases, the lifecycle cost and difficulty of implementing changes increases. Ideally, the addition of SE to a system should not add any complexity to a system; in reality, complexity will be added, which should be minimised and managed.

No current research has investigated the complexity of SE biological mechanisms. This paper aims to address that gap by analysing the complexity of biological SE mechanisms identified in a systematic study using existing engineering tools used to evaluate complexity. The key research questions are:

RQ1 - Where is complexity focused in SE biological system?

RQ2 - What should designers of SE system be aware of when replicating biological SE systems?

1.2. Biological SE system

Self-healing, self-sealing and self-repair mechanisms found in biology have been evaluated in previous review papers (Cremaldi and Bhushan 2018; Speck and Speck 2019; Wegst et al. 2015); however, SE encompasses many more mechanisms. Engineering definitions of SE methods (e.g. self-healing, self-repair, self-reconfiguring) found in (Brooks and Roy 2021) are insufficient because there is a clear difference in the use of self- terms in biology and engineering. The following grouping shown in Fig. 1 is proposed for organising key SE terms to account for biological and engineering perspectives. The terms all fall under the category of SE; the main aim (meaning an increase of evolutionary fitness) of most SE biological processes is to self-adapt. Some SE terms refer to tools utilised in biology, such as self-reconfiguration and self-assembly; other self-terms refer to the resulting mechanism created using these tools. There may be more resulting mechanisms not included or identified here.

It should be noted that biological systems often utilise multiple SE methods (Roy and Brooks 2020), such as self-healing and self-sealing (Speck and Speck 2019). This grouping in Fig. 1 and classification of biological systems under a self-term does not account for species of animal and the system level a response occurs at.

Definition of biological SE terms and a detailed review of SE systems can be found in Appendix A. A summary of 22 key SE biological SE systems identified is shown in Table 1 along with any engineering SE bioinspired research.

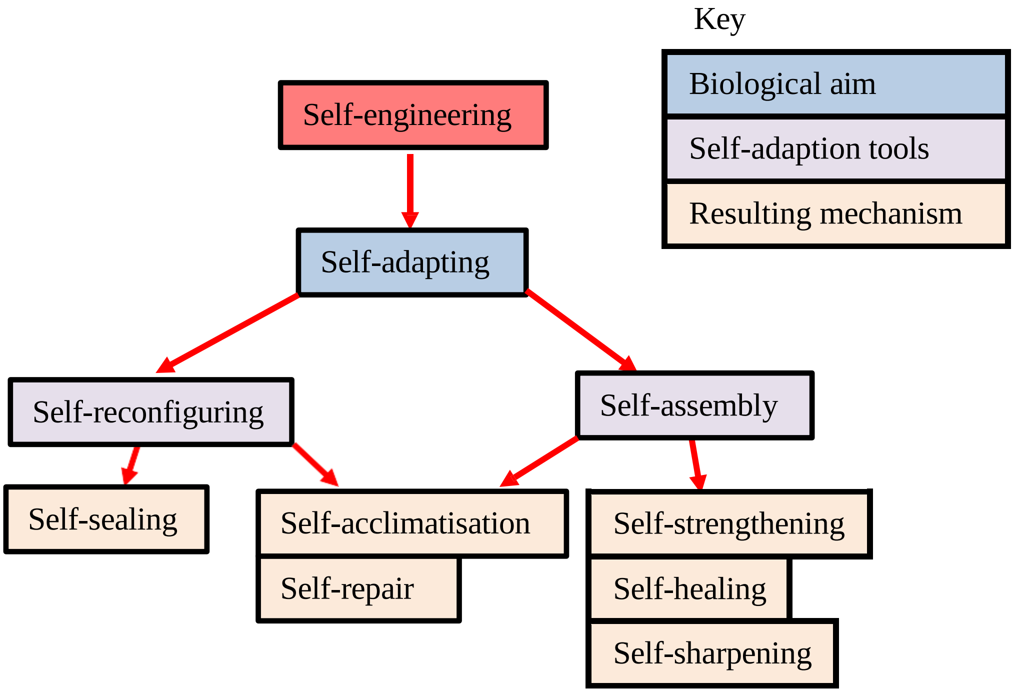

Figure 1 – Grouping of key SE terms from a biological perspective. Some refer to tools which enable self-adaption while others refer to mechanisms which result from using the tools. Arrows show links between groups.

Table 1 – Summary of the 22 different biological systems identified in Section 2 including the key feature and references to bioinspired research where the mechanism was replicated. The final eight systems randomly selected are shown in green.

SE method	Biological system	Key features	Bioinspired research
Self-adapting	Human Finger wrinkling to keep grip	Swelling of outer and contraction of inner skin	
Self-adapting	Human vasoconstriction	Veins regulate blood flow to manage temperature	
Self-adapting	Bar-tailed Godwits adapt for flight	Reduction of gut tissue to make room for fat stores	
Self-adapting	Mammals seasonal moulting	Change coat for different heat transfer properties	
Self-adapting	Animal adaptation to missing limb	Movement recovery when missing a limb	(Bongard, Zykov, and Lipson 2006; Cully et al. 2015)
Self-adapting	Human neuron plasticity	Strengthening of connection to improve signal	
Self-adapting	Skate eye camouflage	Alteration of pupil size to disguise eyes	
Self-assembly	Grass ecosystem adaptation	Other species thrive and replace damaged/lost ones	
Self-assembly	Photomorphogenesis in plants	Growth towards changing light source	(Divband Soorati et al. 2019)
Self-healing	Human skin repair	Veins deliver resources for inflammation, proliferation and remodelling	(Pang and Bond 2005; Norris et al. 2011)
Self-healing	Insect cut healing	Add new cuticle to inner surface	
Self-healing	Mussels anchoring byssal thread	Self-healing using sacrificial bonds	(Ahn et al. 2014; Krogsgaard et al. 2013)
Self-healing	Nacre in molluscs shells	Self-healing using sacrificial bonds	(D’Elia et al. 2016)
Self-healing and self-strengthening	Human bone repair	Osteoclasts remove bone and osteoblast create new bone	(Sangadji and Schlangen 2013)(Orrego et al. 2020)
Self-reconfiguring	Plant bent stalk reorientation	Bending/twisting of stem/flower	
Self-reconfiguring	Moon jellyfish arm reconfiguration	Movement of arms to a symmetrical position	
Self-reconfiguring and redundancy	Hierarchical structure in Animals and plants	Structure made up of redundant cells an tissue can continue operating when damaged	(Bremner et al. 2013; Samie, Dragffy, and Pipe 2009; Teuscher, Mange, and Tempesti 2003)
Self-sealing	Plant internal pre-stressed structure	Bends leaf to seal damaged areas when damaged	(Yang et al. 2018)
Self-sealing	Plant latex discharge and coagulation	Seals outer wounds with latex	(Bauer, Nellesen, and Speck 2010)
Self-sealing	Inter cell layer in plants	Cells pushed to fill wound	(Rampf et al. 2013; Busch et al. 2010)
Self-sharpening	Sea urchin and Shark teeth	Maintain teeth sharp edge through erosion	(Jiang 2014; Killian et al. 2011)
Self-strengthening	Muscle strengthening from training	Bonds strengthen after damage from use	(Matsuda et al. 2019)

1.3. Paper structure

Biology has been inspiring engineers and designers for many years. Usually, Biomimetics or Biomimicry refers to artificially imitating features, mechanisms or elements found in nature (Shu et al. 2011); bioinspired systems aim to replicate or imitate the features of systems found in nature (Speck and Speck 2019). Differentiation of biomimetics, biomimicry and bioinspired can be difficult, and the terms are often used interchangeably or together, in particular when translated from different languages (Speck and Speck 2019; Lurie-Luke 2014; Cremaldi and Bhushan 2018). This paper predominantly uses bioinspired to refer to all three terms.

Initially, in section 2, the complexity of eight biological from Table 1 are evaluated using Suh's complexity theory and axiomatic design concepts to provide initial insight. In section 3, the complexity of the same eight biological systems is evaluated further using the SE complexity framework and expert and student insights. Section 4, discusses the key findings from the paper in relation the original research questions. Finally, in section 6, conclusions and further research areas are presented.

2. Initial evaluation of Biological SE complexity

2.1. Engineering complexity tools

Many authors have attempted to quantify complexity of designs. (Bashir and Thomson 1999) created a crude complexity score for designs based on the number of functions and sub-functions in a design. Later reviews identified three key metrics, size, coupling and solvability, for evaluating design complexity of mechanical systems (Ameri et al. 2008; Summers and Shah 2010). Research into complexity in multi-disciplinary products and system (such as mechatronic systems) also highlighted coupling as a key factor; unexpected coupling in multi-disciplinary systems was noted to occur due to a lack of understanding of physical phenomenon (Tomiyama et al. 2007; Komoto and Tomiyama 2011). Suh's Axiomatic Design (Suh 1999) evaluated complexity of a design by looking at the Functional Requirements (FR) to be met by the design, and Design Parameters (DP) created to meet them. An ideal design was one where the same number of FR and DP are used, the design is uncoupled (meeting the Independence Axiom), and there was a high probability of achieving the specified FR.

A design matrix ([X]) was used to identify coupling in the system between FR and DP, see Equation 1.

$$\{FR\} = [X]\,\{DP\} \qquad (1)$$

Three types of coupling can be found which are shown below. Uncoupled design is the ideal design where each DP can be changed to meet each FR as needed, see matrix in Equation 2. A decoupled design (Equation 3 matrix) is harder to adjust as some FR rely on multiple DP but is still preferable to the coupled design (Equation 4), where it is difficult change one DP without impacting multiple FR.

$$Uncoupled\ Design \qquad [X] = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \qquad (2)$$

$$Decoupled\ Design \qquad [X] = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \qquad (3)$$

$$Coupled\ Design \qquad [X] = All\ other\ matrices \qquad (4)$$

Suh identified four types of complexity, time-independent real, time-independent imaginary, time-dependent combinatorial, and time-dependent periodic (Suh 2005). Definitions of the categories of complexity given by Suh are given below.

- Time-independent Real (Real) - Complexity built into the original design due to coupling between DP and FR, it cannot always be eliminated.
- Time-independent Imaginary (Imaginary) - Complexity added by the designer due to lack of understanding or knowledge of the system's FRs and DPs.
- Time-dependent Combinatorial (Combinatorial) - Unpredictable changes or coupling leads to complexity added over time and reduced FRs met. Examples include degradation of materials or reduction in sensor accuracy, which cause the design to drift from its original design range.
- Time-dependent Periodic (Periodic) - Function periodicity is used to reset the DPs and prevent the system from becoming chaotic. It aims to move a design back towards the original FR.

Suh notes that time-dependent periodic complexity is important for creating a successful design, biology uses periodical cycles to rejuvenate (Suh 2005) (such as sleeping); SE fits well with Suh's theory, it can be classified as time-dependent periodic complexity because it aims to move a system away from time-dependent combinatorial complexity. Axiomatic design has also previously been used to decompose the FR and

DP for a cell about to undergo mitosis, proving further insights into the process and structure and complexity (Lee 2003). Therefore, Suh's complexity theory was chosen to evaluate biological systems in this section. However, the term periodic may not be the best to describe many SE systems because SE systems are sometimes limited to a few responses and not at regular time intervals (only when required).

Knowledge of where complexity is focused in SE biological designs can help designers select appropriate inspiration or highlight potential design problems. Previous designers of bioinspired systems have not utilised engineering complexity theories to help design new engineering systems.

2.2. Methodology

In Table 1, there are 22 distinct SE systems, this is too many to evaluate in one study. A final sample of eight biological systems was created as discussed in section 2.9; these include:

a) Wet skin wrinkles (Changizi et al. 2011)
b) Skin healing from a cut (Cremaldi and Bhushan 2018)
c) Fur malting self-adapting (Walsberg, Weaver, and Wolf 1997; Walsberg 1991)
d) Bird (bar-tailed godwits) migration shrink stomach (Piersma, And, and Gill 1998)
e) Lost limb adaptation (Bongard, Zykov, and Lipson 2006; Cully et al. 2015)
f) Jellyfish self-reconfiguration (Abrams et al. 2015)
g) Self-sealing (bending) (Yang et al. 2018)
h) Grass ecosystem (Allan et al. 2011)

The eight biological systems were evaluated using axiomatic design principles presented by Suh (Suh 1999; 2001). Design matrices were created and used to identify different types of complexity in SE biological systems. The following steps were used:

1. Identify main FR and DP at top level.
2. Decompose FR and DP found in top level (e.g. FR1, FR2 etc)
3. Decompose FR and DP found in step 2 if possible (e.g FR1.1, FR1.2)
4. Construct the design matrix relating DP and FR found in step 1, 2 and 3.
5. Identify real time-independent or time-dependent combinatorial and periodic complexity; imaginary complexity requires insight into the designers thinking and therefore it has not been evaluated for these biological systems.

It should be noted that the axiomatic design method is intended for use during the design of a system not to evaluate an existing system as shown here. These evaluations are dependent on the author's interpretation and abstraction of information found in literature. Some processes have been simplified and different names used when information could not be found. Diagrams and tables are only shown for skin wrinkling to demonstrate the full process steps followed; tables for the seven remaining systems evaluated can be seen in Appendix B.

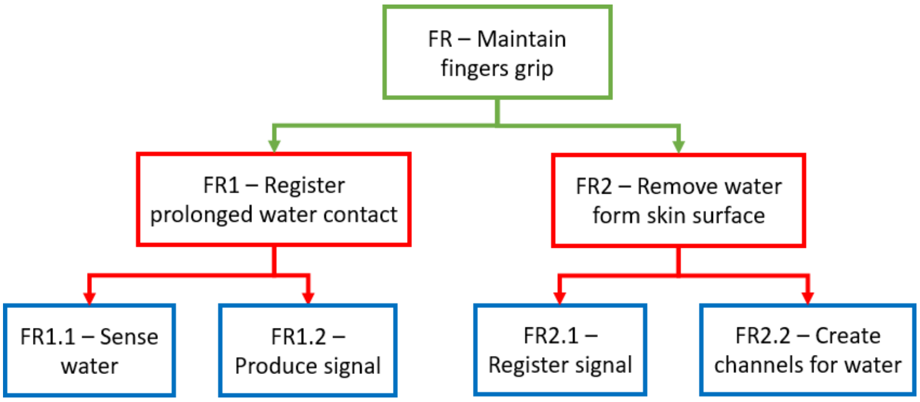

Figure 2 - Diagram of different levels of Functional Requirements for wrinkling of fingers to remove surface water and maintain grip.

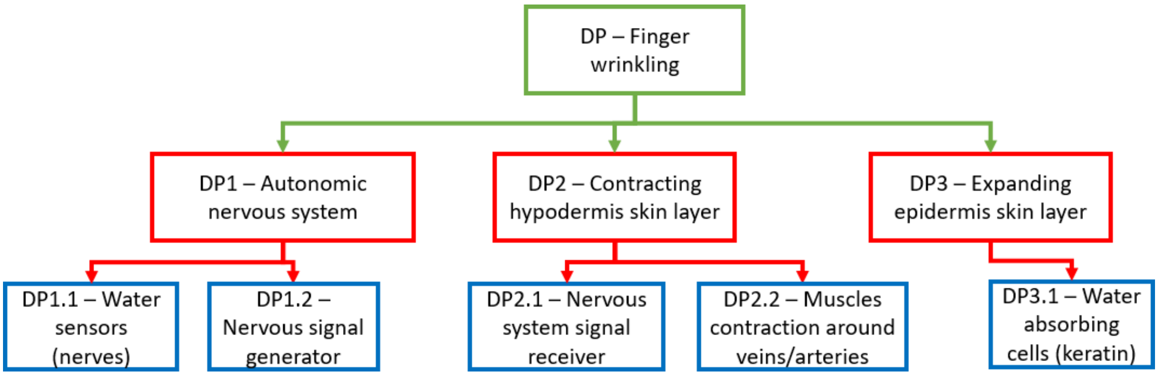

Figure 3 - Diagram of different levels of Design Parameters (DP) for wrinkling of fingers to maintain grip.

2.3. *Skin wrinkling when wet (a)*

The FR identified for skin wrinkling to prevent loss of grip are shown in the diagram in Fig. 2, with the corresponding DP diagram in Fig. 3. Table 2 summarises all the DP and FR in Panel A and shows the design matrix in Panel B. it is clear from the table that the number of DP > FR, called a redundant design by Suh. This redundancy is because multiple mechanisms are needed to create the wrinkling function; winkling relies on the absorption of water and subsequent expansion of the epidermis layer and the constriction of the hypodermis layer. The real complexity in the system is caused by the need for both mechanisms for effective wrinkling. One mechanism relies on no control and one on the autonomic nervous system for centralised control. This interaction between the different mechanisms and their control further adds to the complexity.

The wrinkling itself is a periodic reset that enables the function and grip to be maintained. Damage to the nervous system can prevent the mechanisms from operating. The wrinkling response could be improved by ensuring it can work without one of the key mechanisms driving wrinkling; then, the other could be a redundant backup in case of failure.

Table 2 – FR and DP for wrinkling fingers; Panel A: list of different FR and DP at different levels. Panel B: design matrix for the DP and FR.

Panel A

FR	Maintain grip	DP	Finger wrinkling
FR1	Register prolonged water contact	DP1	Autonomic nervous system
FR2	Remove water from skin	DP2	Contracting hypodermis skin layer
		DP3	Expanding epidermis skin layer
FR1.1	Sense water	DP1.1	Water sensors (nerves)
FR1.2	Produce signal	DP1.2	Nervous system signal generator
FR2.1	Register signal	DP2.1	Nervous system signal receiver
FR2.2	Create channels for water	DP2.2	Muscles contraction around veins/arteries
		DP3.1	Water absorbing cells (keratin)

Panel B

	DP	**DP1**	**DP2**	**DP3**	**DP1.1**	**DP1.2**	**DP2.1**	**DP3.1**	**DP3.2**
FR	X								
FR1		X	0	0					
FR2		0	X	X					
FR1.1					X	0	0	0	0
FR1.2					0	X	0	0	0
FR2.1					0	X	X	0	0
FR2.2					0	0	0	X	X

2.4. Skin healing (b)

Appendix Table B1 summarises all the DP and FR for skin healing. There are more DP than FR, indicating redundant design because multiple components are needed to complete one FR. The design matrix is close to being uncoupled, but real complexity from coupling is present due to all the healing stages relying on the same veins to deliver healing resources. Damage or loss of flow in these veins would delay or stop healing. Combinatorial complexity comes from the healing stage being highly dependent on completion of the previous process; degradation to the initial coagulation stage will cascade and stop further inflammation or remodelling stages from occurring. Periodic complexity comes from the continual replenishment and transport of cells, and many cells perform the same job, which ensures the process continues even with the degradation of some cells.

2.5. Colour changing fur moulting (c)

Appendix Table B2 summarises all the DP and FR for fur malting to change colour and thermal properties. In fur moulting, blood vessels are used to transport the signalling hormone and resources to hair follicles resulting in FRs < DPs; this leads to coupling and real complexity in the system. Periodic refresh is provided by the seasonal change of hair on the animal. The cycle of release of old hair and growth on new hair means that a mistake or loss of function in one season can be repaired the next year. Combinatorial complexity could come from the loss of the triggering hormone, stopping the process triggering at the right point in the year. Some animals do not rely on just one hormone or process to ensure resilience to this kind of failure (Zimova et al. 2018).

2.6. Bird stomach adaptation (d)

Appendix Table B3 summarises all the DP and FR for bird stomach adaptation. The system design matrix is decoupled but not uncoupled. Real complexity is focused in two parts; firstly, the interaction between the nucleus and other parts of the cell and secondly with the migration trigger, which initiates multiple processes simultaneously. Some birds are known to have multiple hormones and signals in repose to season change adding redundancy (and resilience) to the trigger.

The fat stores have to increase, and organs reduce in size simultaneously. Combinatorial complexity could occur if one organ failed to register the imminent migration; this would reduce the bird’s migration preparedness. Periodic complexity comes from the periodic repetition of the process twice a year; assuming the bird survives the failure of the process for one migration, it can occur before the next migration.

2.7. Four legged lost limb adaptation (e)

The design matrix in Appendix Table B4 shows a coupled design; DP1.1, the central nervous system is needed for two FRs: to process and transmit signals. Real complexity is caused by all legs and the central nervous system being needed to complete the key functions (walking or running). If one leg is removed, the number of DPs falls, leaving FRs >DPs, reducing how effectively the FR are met. Combinatorial complexity can come with age, which can lead to the degradation of the nervous system and balancing ability, impacting the ability to walk and adapt to a missing limb. Period complexity could come from the constant trial-and-error, learning and adaption of the animal, or the creation of new neurons and connections in the brain to cope with walking on three legs. However, neurons do not frequently replenish like other cells in the body.

2.8. Moon jellyfish self-reconfiguring (f)

Appendix Table B5 summarises all the DP and FR for jellyfish reconfiguration. At least four arms are needed for the juvenile jellyfish to grow into a healthy adult jellyfish. If arms were removed, fewer spare arms would be shown in the DP. The design matrix relating FR and DP shows a coupled design. The reconfiguration is driven purely by the mechanical forces from the contraction and relaxation of the jellyfish arms. Therefore, arms and arm muscles are involved in providing thrust for swimming and reconfiguration. If there were only four arms left, this would lead to the three FRs (FR1.1, 2.1 and 2.2) being satisfied by two DPs (DP1.1 and DP2.2), an insufficient design. However, with only one limb missing, the design would be an example of a redundant design because there are more DPs than FRs (DP>FR). The real complexity in the system comes from the interaction between the arms and where they join (the manubrium). Each arm relies on the others being there to keep the symmetric pattern and the force balanced. Combinational complexity could come from the loss or degradation of the arms or muscles. Damage to arm muscles will impact swimming and stop reconfiguration; this is demonstrated in (Abrams et al. 2015) when jellyfish are given a muscle relaxant disabling swimming and reconfiguration functions. The reconfiguration of the arms is an example of periodic complexity and relies on repeated contraction and relaxation of muscles. However, the response is not periodic; it only occurs as long as two or more arms are left, and swimming ability degrades every time an arm is lost.

2.9. Self-sealing plant leaf by bending (g)

The main FR and DP were only decomposed once because of a lack of knowledge of this system below this level. The design matrix in Table B6 shows a coupled design; real complexity occurs because of the need for multiple pre-stressed and pre-strained layers with different a elastic modulus to provide the closing force. Combinatorial complexity comes from the degradation of the cells in each layer which could occur due to a lack of water or sun. Cells can be renewed periodically, but the process cannot be reset once used because the whole leaf structure is altered.

2.10. Grass ecosystem

For the grass ecosystem, only three categories are considered, foliage, herbivores and predators. They are grouped in ‘species 1’ and ‘species 2 to N’. However, in reality, there would be many more species and categories, such as insects and birds to also consider. The design matrix (Appendix Table B7) shows a coupled system due to the interaction between the foliage, herbivores and predators. The real complexity occurs because each category relies on at least two other categories, one to provide resources for its growth and one to regulate its growth. Combinatorial complexity can come from many sources such as weather change, environmental damage or human actions; even introducing more nutrients such as fertiliser can upset the balance of the system. Loss of one species can be compensated for by other species in the system. However, this is dependent on a periodic refresh of the system in the form of species breeding and dying. The greater the number of species in each category, the greater the resilience of the system.

2.11. Discussion of results

Real, combinatorial and periodic complexity identified for each biological system is summarised in Table 3. Analysing the FR and DP for different biological systems is useful because it helps highlight the key functions biological systems aim to complete and how they are accomplished. The design matrices highlight the complexity and where different mechanisms or components are interacting. From analysing these eight systems, there are four key notable recurring features related to complexity.

- *Redundancy* is present in many biological systems; this is often demonstrated by the way DPs>FRs is more common than DPs<sFR.
- *Coupling* is always present in the biological system. None of the systems evaluated shows complete uncoupling of FR and DP or the same number of DP and FR required for an ideal design, indicating either that nature has not always found the optimum design even with thousands of years of evolution or that the ideal design is not an uncoupled one.

- *Real complexity* is often focused on a component controlling multiple processes (such as the cell nucleus or central nervous system) or one component used in multiple processes (such as veins and arteries).

Table 3 – Summary of real, combinatorial and periodic complexity identified for each of the eight biological systems reviewed.

Biological system	Time-independent real complexity	Time-dependent combinatorial complexity	Time-dependent periodic complexity
a)	Multiple mechanism with different control used to drive wrinkling	Failure of one mechanism stops process	Skin cells refresh regularly to repair damage and wrinkling repeats many times a day
b)	Interaction between healing stages and blood vessels used for transporting all resources	Interruption or delay to one stage impacts all healing stages	Many types of cell are constantly being used and replenished during healing stages
c)	Blood vessels used for transporting multiple resources	Age or disease may degrade animals ability to register season change and produce new fur	Hair and fur is constantly being replenished every year and not just in moulting seasons
d)	Processes in multiple organs have to occur simultaneously based on one trigger	Failure of one organ to register the required change needed for migration	The process occurs periodically twice a year
e)	Combination of all legs and nervous system needed to move effectively	Further loss of balance and nervous system	Repeated trial, error and learning process needed to walk
f)	Interaction between different arms	Loss or damage of muscle function	Contraction and relaxation of muscles driving reconfiguration
g)	Multiple pre-tensioned layers needed to close wound	Degradation of cells providing tension in layers within the leaf	Cells in the leaf can be replenished but the mechanism cannot be reset once triggered
h)	Interaction between different categories and species	Environment change/ degradation, human actions, weather change or introduction of a new species	Death and birth of new generations of animals or plants

- *Periodic refresh* relies on a cycle of new cells or organisms replacing damaged or dying ones. This replacement of lots of parts continually is not practical in engineering systems.

It should also be noted that only eight systems are evaluated here, which is not comprehensive enough to conclude that all biological systems have these features.

Suh’s method of evaluating complexity is limited to only a few types of complexity in the system, meaning other complexity features might be missed. Also, as stated in Suh, n.d.; (2001), the introduction of real complexity could occur because of inappropriate selection of FR or DP by the designer or, in this case, the author.

3. Further evaluation and insight into SE biological complexity

The initial investigation highlighted some of the systems’ complexity, but the method used was not specific to SE systems and designed primarily for evaluating engineering designs. A further evaluation was carried out using the SE complexity framework. This framework is simpler and requires less training than Suh’s; therefore, participants were included to provide a wider range of opinions about complexity.

3.1. Self-engineering complexity framework overview

The SE complexity framework presented and validated in (Brooks and Roy 2020) involves three key factors used to assess the complexity of SE systems.

1. *Repeatability* – This does not refer to scientific repeatability but the quantity of times a response can occur.
2. *Redundancy* - Many biological and engineering SE systems utilise redundancy; adding lots of spare components can improve robustness, but it adds complexity to the system.
3. *Self-control* - This is the most difficult to score as there is a wide range of control strategies used. SE systems with a reactionary response with no control are given the lowest score. Centralised control is given a medium-level score and multiple interacting controllers a high complexity score.

Table 4 from (Brooks and Roy 2020) provides more detail on the framework and characteristics of a high, medium, and low complexity SE system.

Table 4 – Low medium and high defined for each complexity factor in the SE complexity theory, replicated from (Brooks and Roy 2020)

Factor	**Complexity**		
	Low	**Medium**	**High**
Repeatability	System can respond only a few (maybe 1-3) times to loss of function	System can respond multiple times to a loss of function (the loss can be different each time).	At the highest level, it can respond many times or an unlimited number of times.
Redundancy	At the lowest level no redundancy is utilised for the SE mechanism.	Some redundancy is utilised to ensure the SE system can continue to respond.	There is lots of redundancy which is used as part of the SE mechanism.
Self-control	At the lowest level a SE response is reactionary and no control is used.	There is some control which manages the SE response, the system will be centrally controlled.	This is where more complex control is used. Different parts may have different control methods which are interacting and communicating, possibly creating complex (emergent) behaviour.

3.2. Methodology

Participants were asked to rank the eight biological SE systems under each complexity factor (redundancy, repeatability and self-control) separately. Participants were provided with a description of each of the eight biological systems, a picture, a link to the original information source, a table to fill in rankings and a description of the complexity framework they were to use. If participants felt they had insufficient knowledge or information to make a judgment, they could choose to write NS rather than a rank in the table provided; otherwise, they ranked 1 for highest complexity to 8 for the lowest complexity. Two groups of participants were used, one of nine experts and one of 23 students. Due to the different number of participants, the exercise was presented differently to each group.

Experts were recruited from a range of disciplines to get a broad range of perspectives of people who may use the complexity framework; see Table 5 for experts' experience and research area. Experience in years is rounded to the nearest year and includes years of study in the relevant area of expertise. Experts were sent all the information for the exercise by email and asked to complete the exercise; interviews were conducted with experts after the task was completed to gain further understanding of the reasoning behind different rankings. Questions mainly focused on the experience of using the framework and the reasoning for high and low choices.

Student participants were recruited from final-year students studying for a degree in Biomimetics at the Hochschule Bremen, which includes training in chemistry, physics, biology, engineering and biomimetics. Students completed the exercise during an online class; they were provided with descriptions of biological systems before the session; during the session, the concepts of self-engineering and the framework were introduced in a presentation. Interviews were not possible with students due to the larger number of participants but students were asked to provide descriptions of their reasoning to check the scoring method used. Some students were also followed up after the exercise to get further information where it was needed.

Table 5 – Table summarising expert experience and research area.

Number	Main area of research	Experience (Years)
1	Mechanical, Manuf. & Biomedical Eng.	45
2	Bioinspired design	5
3	Biological Chemistry	23
4	Biomechanics	18
5	Design	30
6	Biomechanics	4
7	Biomedical Engineering	16
8	Biomimetics	5
9	Robotics and Autonomous Systems	33

3.3. Results

Using the results from the excise, a mean (μ), standard deviation (SD) and mode were found for each biological system and category; these values are compiled in Table 6. Values for μ and SD values are normalised to $\boldsymbol{\mu_N}$ and SD_N using Equation 5 so that one becomes the highest complex and zero the lowest complexity score.

$$\frac{x_{Lowest\ possible\ rank} - x}{x_{Lowest\ possible\ rank} - x_{Highest\ possible\ rank}} = \frac{8 - x}{8 - 1} = x_N \qquad (5)$$

Table 6 – Table showing results of exercise using SE complexity framework with students and experts. μ_N, SD_N and the number of responses which were not NS (Size), are shown for each group. The p-value from a KS tests also indicates how similar the distributions of scores were. While k indicates the average Cohen's Kappa score.

	Student			**Expert**			**KS P-value**	**Average *k***
	μ_N	SD_N	**Size**	μ_N	SD_N	**Size**		
Repeatability								
a) Wet Skin wrinkling	0.96	0.09	23	0.86	0.14	9	0.06	0.31
b) Skin healing from a cut	0.80	0.12	23	0.65	0.23	9	0.47	0.35
c) Fur malting	0.78	0.18	23	0.73	0.18	9	0.99	0.22
d) Bird shrinking stomach	0.65	0.21	22	0.66	0.23	8	1	0.16
e) Lost limb adaptation	0.11	0.13	23	0.11	0.14	9	1	0.37
f) Jellyfish self-reconfigure	0.44	0.24	20	0.38	0.27	8	0.92	0.15
g) Plant bending to seal	0.49	0.18	23	0.54	0.28	9	0.55	0.15
h) Grass ecosystem	0.59	0.26	21	0.88	0.26	8	0.02	0.12
Redundancy								
a) Wet Skin wrinkling	0.53	0.39	19	0.44	0.19	9	0.1	0.05
b) Skin healing from a cut	0.71	0.24	22	0.52	0.40	9	0.57	0.11
c) Fur malting	0.57	0.27	17	0.51	0.29	9	0.43	0.12
d) Bird shrinking stomach	0.41	0.25	20	0.54	0.21	8	0.44	0.14
e) Lost limb adaptation	0.38	0.39	23	0.33	0.31	9	0.88	0.14
f) Jellyfish self-reconfigure	0.53	0.24	23	0.43	0.31	8	0.84	0.1
g) Plant bending to seal	0.51	0.26	22	0.41	0.30	9	0.64	0.14
h) Grass ecosystem	0.82	0.26	21	0.79	0.36	9	1	0.35
Self-control								
a) Wet Skin wrinkling	0.41	0.36	22	0.54	0.38	8	0.37	0.11
b) Skin healing from a cut	0.52	0.33	23	0.52	0.35	8	0.92	0.11
c) Fur malting	0.45	0.25	22	0.52	0.22	8	0.96	0.15
d) Bird shrinking stomach	0.56	0.27	20	0.55	0.25	8	1	0.13
e) Lost limb adaptation	0.80	0.23	23	0.82	0.25	8	0.74	0.21
f) Jellyfish self-reconfigure	0.56	0.28	20	0.18	0.25	8	0.04	0.08
g) Plant bending to seal	0.38	0.23	22	0.16	0.23	9	0.1	0.14
h) Grass ecosystem	0.45	0.43	20	0.27	0.35	9	0.35	0.17

The $\boldsymbol{\mu_N}$ value is useful for showing what the average overall rank was but does not sufficiently show the spread or range of choices made by participants; this is better demonstrated with the SD_N. When calculating $\boldsymbol{\mu_N}$ and SD_N, the rankings of NS were not included. Graphs are plotted using the normalised mean with each factor on one axis. Fig. 4 shows redundancy vs self-control, and Fig. 5 shows repeatability vs redundancy.

Size in Table 6 is the number of participants who did not write NS. By converting the ranks to normalised number scores, a Kolmogorov–Smirnov (KS) test can be used to compare the distributions of scores of the different groups. The KS test was performed on MATLAB, and p-values calculated for each biological system in each category. The p-value can be used to indicate how similar the answer distributions were; when the p-value was close to 1, the distribution of answers was very similar, while close to 0 indicates the distributions were very different.

Table 6 also shows the inter-rater reliability measured using the Cohen's Kappa (k) (Kilem Li Gwet 2014; Hallgren 2012); k is calculated for each expert ranking in

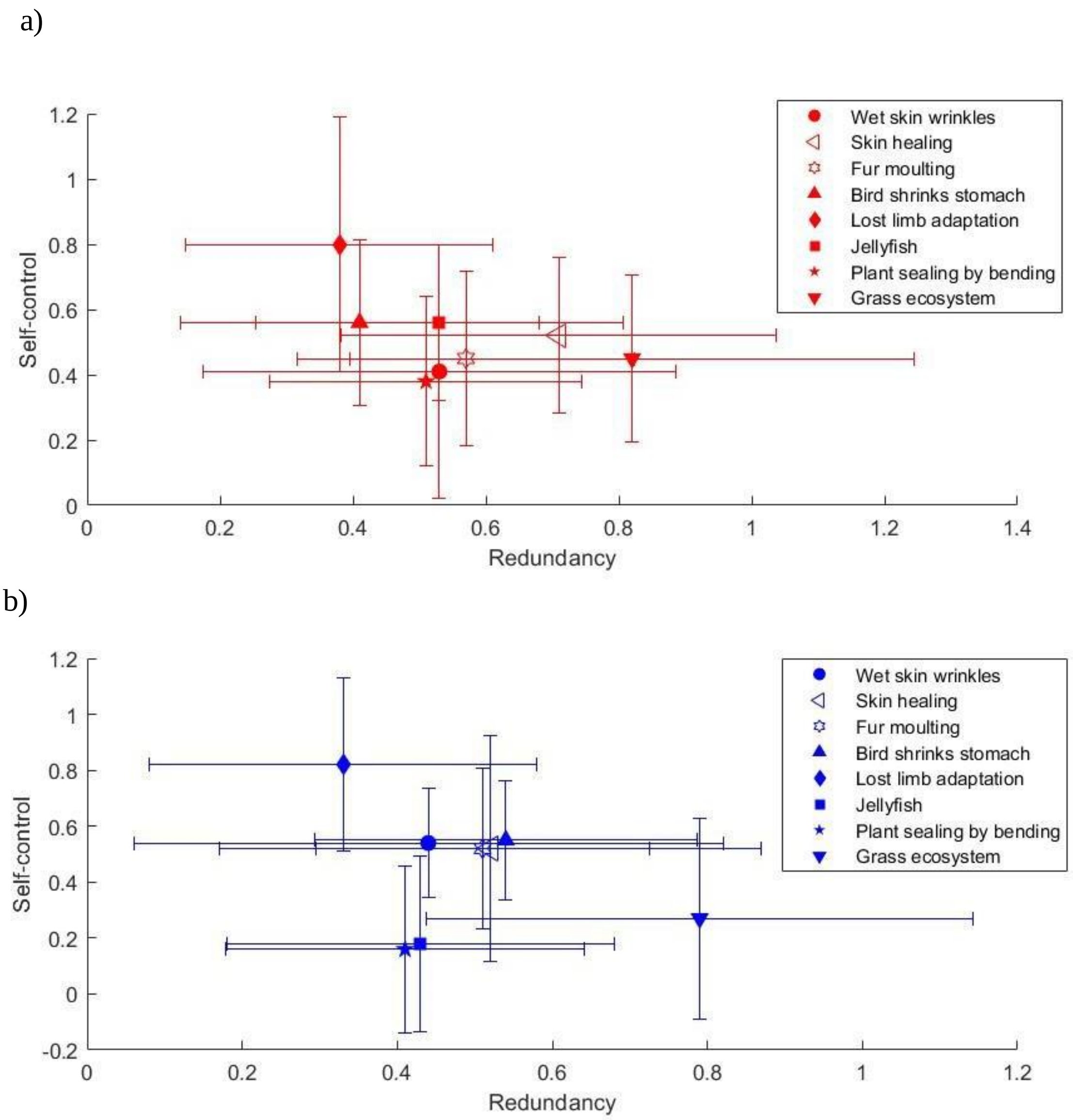

Figure 4 – Graphs showing the normalised mean for redundancy vs self-control for each of the biological systems. Graph a) is student while b) is expert rankings.

relation to the student rankings given. The average value of k is then shown in Table 6. Equation 6 was used to find k; P_o is the observed agreement between students and experts (e.g. 0 for no ratings agreeing and 1 when all ratings agree); P_e is the probability of there being random agreement.

$$k = \frac{P_o - P_e}{1 - P_e} \qquad (6)$$

Values of k closer to 1 show more agreement between raters. Cohen's Kappa is used to compare two raters' scores but can not tell disagreement within each group or raters; for that, Fleiss' Kappa (k_F) was applied. The k_F for all expert raters was 0.218, while for

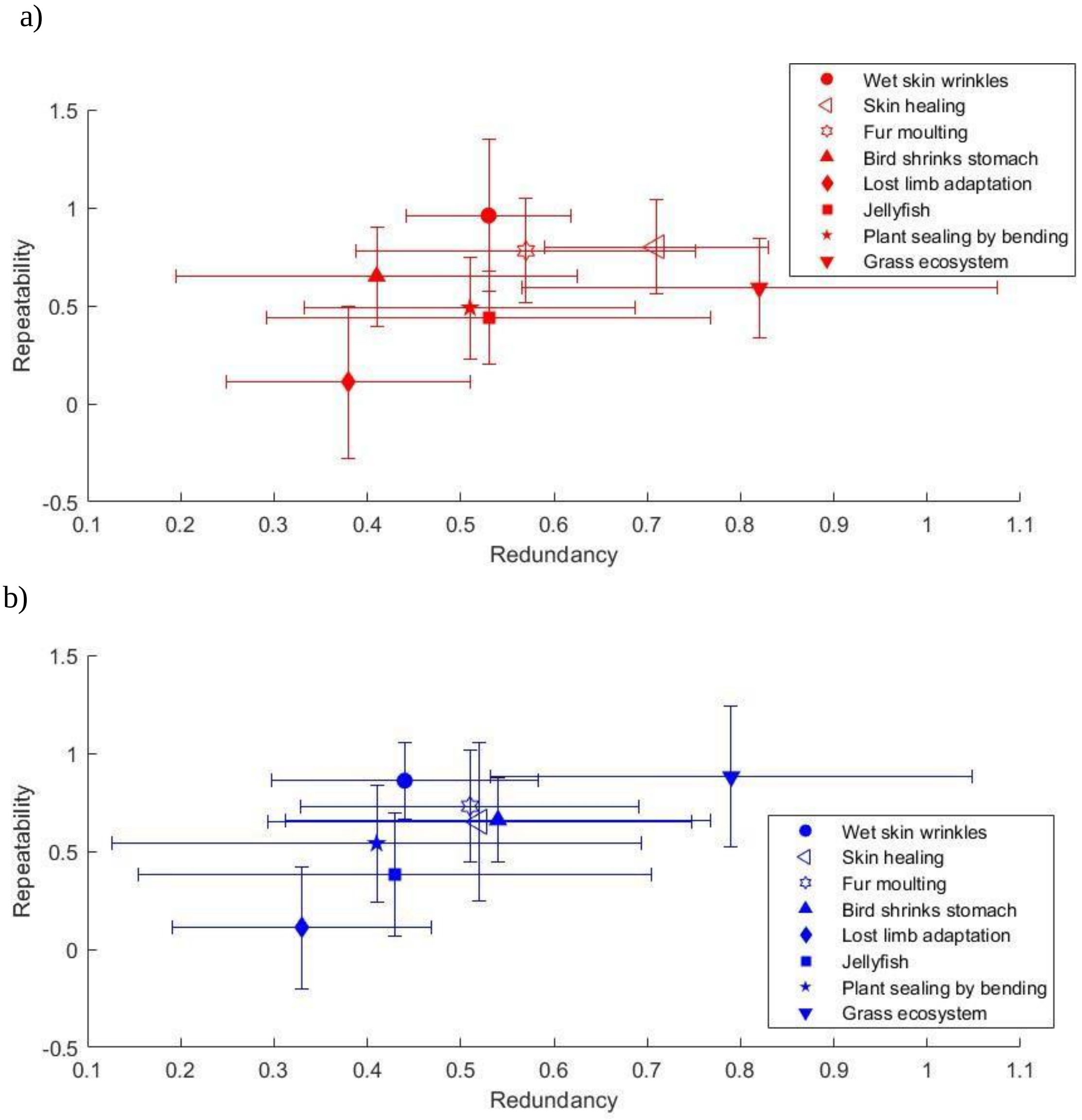

Figure 5 – Graphs showing the normalised mean for redundancy vs repeatability for each of the biological systems. Graph a) is student while b) is expert rankings.

students, it was 0.145; both these values are above 0 but low, indicating that there is some moderate agreement within each group.

A final score for each biological system evaluated was calculated by summing the $\boldsymbol{\mu_N}$ of each of the three factors ($\sum \boldsymbol{\mu_N}$) for each biological system. Rankings and final score for students and experts are shown in Table 7 Panel A and B.

Table 7 – Final ranking using the sum of all normalised means calculated is shown in Panel A for experts and Panel B for students.

Panel A

Biological system	**Experts □ μ_N**
h) Grass ecosystem	1.94
a) Wet Skin wrinkling	1.84
c) Fur malting	1.76
d) Bird shrinking stomach	1.75
b) Skin healing from a cut	1.69
e) Lost limb adaptation	1.27
g) Plant bending to seal	1.11
f) Jellyfish self-reconfigure	0.98

Panel B

Biological system	**Studnets □ μ_N**
b) Skin healing from a cut	2.02
a) Wet Skin wrinkling	1.91
h) Grass ecosystem	1.86
c) Fur malting	1.80
d) Bird shrinking stomach	1.62
f) Jellyfish self-reconfigure	1.53
g) Plant bending to seal	1.38
e) Lost limb adaptation	1.29

3.4. Discussion of results

3.4.1. *Repeatability*

Overall repeatability scores had the highest agreement among experts and students, shown by high k. Similar $\boldsymbol{\mu_N}$ scores were chosen by experts and students for repeatability; one clear exception shown in Table 6 is grass ecosystems which experts scored higher complexity. The difference in rating is also shown by the lowest k value of all systems in repeatability. Students scored it lower, often citing the fact that it relied on the number of species, while other mechanisms such as hand wrinkling, fur moulting and bird stomach shrinking did not have the same constraints. Grass ecosystem’s reliance on redundancy to respond was also highlighted in the initial review in Section 3. Experts explained the higher score for the grass ecosystem due to the higher effectiveness of each repair and that the system has survived for 1000s of years with many species gained and lost in that time. For both groups, grass ecosystems received a wide range of scores; it was noted by two students and two experts that the repeatability could not be clearly defined without knowing the number of species in the system. This link between repeatability and redundancy can also be seen in Fig. 5 where μ_N for each factor appears to follow a linear relationship.

The highest level of agreement (shown by k) between groups was for a high repeatability complexity score for skin healing and wet skin wrinkling and a low score for lost limb adaptation.

3.4.2. *Redundancy*

Student scores for wet skin wrinkling varied, shown by the high SD_N in Table 6 and the large number of NS responses. Students and experts both noted this system was hard to score as some redundancy was evidently present and needed in the form of spare cells, veins or nerves; however, as noted in Section 3.2 the redundancy in the system also comes from multiple mechanisms used to complete one function.

Uncertainty in redundancy scoring was also seen with lost limb adaption; participants tended to favour a low score as there was only one redundant leg on an animal before it could not walk at all. However, almost 1/3 of both groups did put a higher complexity score, citing that the redundancy was vital for the SE response. This is true but deviates from the SE complexity framework, which focuses on the quantity of redundancy. Others noted that redundancy required in the remaining limbs and the body needed to support a missing limb added to the total redundancy needed.

For experts, skin healing presented the largest variation in scores with the highest SD_N. High complexity scores were given by experts focusing on the large quantity of redundant cells present; a large amount of redundancy needed in the design was noted in the initial review in Section 3.3 and by most student participants. Experts often gave low or middle scores, citing that excess cells were either all utilised or that the skin healing was not as dependent on the redundancy as other systems. The largest difference between student and expert $\boldsymbol{\mu_M}$ was seen with skin healing.

Participants in both groups noted they struggled to score the fur moulting and bird stomach shrinking because they found it difficult to identify what could be considered redundancy in these systems. This led to a wide range of scores and a difference in the mode and distribution of scores given. In the initial evaluation, it was noted that both systems rely on a continual replenishment of cells to prevent degradation of the SE system; however, no redundancy was noted in the design matrix. The highest $\boldsymbol{\mu_M}$ and highest k for both groups showing agreement in scores, was for grass ecosystem. Little agreement in rankings was seen for repeatability in all other systems, especially skin wrinkling, which had the lowest agreement.

3.4.3. *Self-control*

Self-control was the category which participants most frequently mentioned they found hardest to score, noting that the framework or the information provided did not always have enough detail. For wrinkling fingers and skin healing, there was a high SD_N and a low k, showing a wide range of scores given and a low level of agreement between experts and student. Experts tended to score wrinkling higher, identifying that the multiple mechanisms controlling the process made it more complex; these interacting mechanisms were also highlighted as adding real complexity in section 3.2. Experts tended to refer to the framework provided more frequently with self-control; in contrast, students were more prone to use their own interpretation of self-control. This difference could be due to experience or how the exercise was presented.

With skin healing, fur moulting, and the birds’ stomach adaptation, participants in both groups found it difficult to identify the controlling mechanisms, with both groups indicating in comments that they felt they were not confident in their answers given.

Large SD_N are shown in Table 6 for grass ecosystems because participants in both groups chose either a high score or low score; this difference is linked to how participants interpreted self-control. Participants in both groups often interpreted self-control as the amount of influence and awareness the biological entity has over the SE response. Therefore, plant-based systems with no conscious control scored lower complexity than animal and human systems, where thought and active decisions are made. Interactions between many plants in the grass ecosystem were either observed as simple reactionary responses or highly complex interactions which are hard to predict and replicate; this led to low or high complexity scores, which averaged out to lower than expected self-control complexity scores.

The largest difference in $\boldsymbol{\mu_N}$ in Table 6 was shown for jellyfish reconfiguration and then plant bending, with experts having $\boldsymbol{\mu_N}$ = 0.18 and 0.16, and students scoring $\boldsymbol{\mu_N}$ = 0.56 and 0.38 representatively. Students tended to consider the whole system life, including how these mechanisms were built and created when considering control; this is an interesting approach but did complicate the simplicity of these responses, which are largely reactionary. Low values of k (0.08 and 0.14) are also seen for jellyfish and plant bending, indicating little agreement in scoring by experts and students.

3.4.4. *Final complexity scores*

The final complexity scores presented in Table 7 have some clear similarities. Both groups had grass ecosystems and wet skin wrinkling in their top two, while also putting jellyfish reconfiguring, plant bending to seal a wound and lost limb adaptation in the bottom three. This demonstrates some overall consistency when ranking the complexity of systems. The largest difference in the final ranking is skin healing from a cut. For students, it came out top, but only 5th overall for experts. The k values show that this difference is driven by differences in rankings redundancy and self-control.

Fig. 4 and 5 show the final scores for all the systems for both students and experts. The largest differences in position on the graph of the final scores is for skin healing, bird stomach adaptation and jellyfish reconfiguration. This is also seen in the k values for these systems, which are often below 0.15 for two or all three of the framework factors.

3.5. Common problems with framework

Common problems which were either noted by participants or from analysing the results are summarised.

1. When two biological systems have similar attributes, it was difficult to differentiate which to score higher. Participants tended to add additional rules to enable differentiation; although many of these rules were logical, it led to differences. Further refinement of the framework or more detailed knowledge of each biological system could help reduce this problem. It may also help participants to decide if they have access to the results from (or

completed themselves) the initial evaluation in Section 3. This was not done because it would have required more knowledge of Suh's complexity theory.

2. It was highlighted by three participants that the language used in the exercise information impacted their choice. For example, words like redundant or spare could have led to higher redundancy scores for those systems.
3. Scores were influenced by personal experience and knowledge. Many students noted that they scored wrinkling fingers high because they see it occurring almost every day, but other SE responses, such as those in animals, are less visible and subsequently might have been scored lower. Experts and students tended to draw on their own knowledge when they felt there was insufficient knowledge provided, leading to differences in scores related to what systems participants had worked on previously.
4. Three experts and two students noted that the biological SE mechanisms are applied at different system levels, which made it harder to compare them effectively. For example, comparing the grass ecosystem, a system-level response, to the plant bending, a material-level response, can be difficult. In future work, the examples could be changed to be the same system level.

3.6. Summary

An evaluation using nine experts and 23 students was performed using the complexity framework presented by Brooks and Roy, which uses three key factors: repeatability, redundancy and self-control. Results from each group were compared. The closest agreement between the two groups was with repeatability scores. For redundancy and self-control, the framework produced less consistent student and expert scores, shown by the lower k values. Final complexity rankings for the biological systems were created and are shown in Table 7. The biggest differences between experts' and students' final $\boldsymbol{\mu_N}$ values were for skin healing (in redundancy), jellyfish reconfiguration (in self-control) and grass ecosystem (in repeatability).

The SE complexity framework could be utilised to help designers take inspiration from biology by enabling them to break a system down into three key complexities. Certain situations will require reduced complexity of specific factors. For example, suppose a repair needed to occur without close control or monitoring because it was not possible; in that case, a designer could take inspiration from systems with a low self-control score, such as a plant bending to seal a wound. For systems where redundancy has to be minimised due to design constraints (such as during space exploration), a designer could select systems with a low redundancy score, such as lost limb adaptation.

4. Final discussion and insights

4.1. RQ1 - Where is complexity focused in self-engineering biological system?

In both previous section a summary is shown highlighting the key areas of complexity in the biological systems evaluated. These are summarised in the list below:

- Multiple mechanisms or sub-systems (groups of cells or orangs) often make up a SE responses and they are reliant on communication from a previous process or other sub-systems. Break down of this communication or series of processes stops or limits a SE response (see section 2).
- Most SE responses are predominantly reliant on death and creation of new material such as cells (see section 2). All SE systems and maintained by replenishment of cells or materials of some form.
- Biological SE response that can only occur a few times (low repeatability) also seems to have lower redundancy (shown in Fig. 4).
- Redundancy is often used and seen to increase in line with repeatability of a SE mechanism (shown in Fig. 5).
- The complexity of biological mechanism control is the hardest aspect to identify and evaluate (discussed in Section 3)

4.2. RQ2 - What should designers of SE system be aware of when replicating biological SE systems?

From reviewing both methods used to evaluate SE biological systems, a set of rules is proposed for designers to identify and handle complexity when replicating or taking inspiration from SE biology systems. These proposed design rules are intended to address RQ2.

1. **Focus on the key function returned** – There are many examples of self-healing and self-repair in nature; when searching for examples for bioinspired SE it is important to focus on the key function being returned. Many examples of biology presented on databases such as

AskNature.org focus on creating robust materials or systems; these are designed to withstand damage or degradation while SE aims to respond to it.

2. **Identify redundancy** – Previous studies of bioinspired design have cautioned designers to be wary of the high level of redundancy in biology (Hinegardner and Engelberg 1983). However, it is valuable to identify the redundancy in the system, how it is being used and most importantly if it can be reduced. For example, skin healing involves many types of cells and may initially seem too complex to replicate. However, the design matrix in the Appendix highlights that the system could be simplified with just three DP to complete the three key FR, 1) to identify the damage, 2) to remove debris and 3) to build the new material.
3. **Evaluate how the SE response is reset** – This was evaluated by looking for the periodic time-dependent complexity in Section 3 and the repeatability in Section 4. It is important to identify early if the repeated SE response relies on cell regeneration because this is currently beyond the scope of engineering. The reconfiguration of the jellyfish does not rely on cell regeneration and is therefore much easier to replicate and utilise. The next step is to evaluate if this cell regeneration can be removed or replicated in another way. For example, a bird’s stomach adaptation occurs when cells in the gut die and grow as the size requirements change. However, the same function could occur in engineering due to material elasticity.
4. **Identify coupling** – Breaking the system down into DP and FR helped identify coupling, where multiple components are used for one process. As discussed in Section 3.10, this knowledge can help design a less complex uncoupled solution. Using the SE complexity framework in Section 4 did not identify coupling.
5. **Find what starts and ends SE** – In Section 4, reviewers struggled to identify the self-control managing a biological system; it can be easier to consider what triggers and stops the process occurring. For some examples, like plants which release latex to seal a wound, this can be

easy to identify, while other processes like skin healing can be more complicated.

This is not an exhaustive list of rules, especially as only eight biological systems are evaluated in detail. However, it provides a starting guide for designers of bioinspired SE systems. Further studies could focus on validation of these rules with new bioinspired designs.

4.3. Limitations of review

It is important to note that no unified ranking or criteria for measuring complexity in biology exists. This makes it challenging to validate the insights and results shown. However, validation can be discussed in relation to the method used. Suh's Axiomatic Design used initially has been used previously to evaluate biological systems (Suh 2005), providing a good template method to replicate in this study. However, the SE complexity framework has only been used in engineering systems design (Brooks and Roy 2022). The factors used in the SE framework are similar to those used in other biological complexity evaluations. Redundancy is similar to previous research, which utilises the number of parts in biological systems to measure complexity (Hinegardner and Engelberg 1983). The other factors (repeatability and self-control) have not been used in previous evaluations of biological complexity, although similar properties of the number of connections or the organisation in a system have been proposed as measures (Grandpierre 2011). The fact that these similar measures have been used by previous biological complexity studies provides some validation that they are suitable for identifying complexity but does not fully validate the results or the final rankings shown in Section 3.

4.4. Discussion of usefulness

Some of the underlying characteristics in biology, such as small mechanism sizes or material and cell growth, are beyond engineering capabilities. However, previous studies of nature have yielded useful new products that have drawn on key chemical processes, design features or structures found in nature with these characteristics (Wegst et al. 2015). It is still useful to understand complexity before designing a SE engineering system. One example of where more knowledge on complexity could have helped is the design of vascular self-healing materials; despite many research studies, these materials are not utilised commercially. Evaluation in Sections 3 and 4 showed that the repair in skin healing depends on redundancy (ranked second highest for students and third for experts). However, self-healing vascular composites are often cited as being for aircraft or space applications, where the space and weight needed for redundancy are limited. Early evaluation of complexity may have led to better use of initial applications or demonstrators where weight and space are less of an issue, such as buildings.

Currently, the SE framework only considers scale in terms of redundancy, not physical size or number of parts. Replicating smaller SE mechanisms in engineering is often impossible due to manufacturing limitations. However, smaller biological scales should not be ignored as they can still be replicated successfully at a larger scale. Replicating smaller cell mechanisms can also be difficult as they may rely on small interaction forces or chemical processes which do not scale, or there may be missing knowledge which is only theorised. Neither manufacturability nor detail of knowledge available are considered in the complexity frameworks tested in this research but may need to be included in future evaluations.

5. Conclusion

In total, 22 different biological systems with SE features are identified. Eight biological SE systems were evaluated using two different complexity methods in a systematic study. In Section 3, Suh's well-established Axiomatic design and complexity theory is utilised to provide initial insights and understanding of the complexity of the eight biological systems. Biological systems were broken down into FR and DP; a design matrix is then used to identify how the FR and DP are linked. Four key features where complexity is focused were commonly noted using Suh's method. The first was that redundancy is commonly present in the biological system. The second was coupling, with multiple components used to complete one function. Third, complexity is often focused on where one component is involved in multiple key functions (such as a nucleus or blood vessel). The last feature was that processes are periodically repaired and refreshed by the cycle of death and growth of cells.

The second complexity framework utilised was the newer SE complexity framework created specifically for evaluating SE systems (see Section 5). The framework focuses on three key factors, repeatability, redundancy and self-control. Nine experts and 23 students used the framework to rank the complexity of eight biological SE systems. Participants noted that self-control was the hardest to evaluate, indicating that the framework needs further detail and refining for this factor; for example, further rules could be created to help separate systems when they have similar attributes. The biggest differences in experts' and students' final mean scores were noted for skin healing redundancy, jellyfish reconfiguration self-control, and grass ecosystem repeatability. Generally, the final rankings created from expert and student rankings were similar apart from skin healing.

In the last section, key areas where complexity is focused were highlighted and five proposed design rules were proposed using insights gained from Sections 2 and 3. The rules aim to help designers identify and create new bioinspired SE systems. Future work could focus on using these rules and results from Section 2 and Section 3 to design a new bioinspired SE system from one biological system. The resulting design could be compared to one created by a different design without the rules or complexity framework being used.

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