A bio-inspired reinterpretation of symbiotic human-robot collaboration in assembly processes

Original
A bio-inspired reinterpretation of symbiotic human-robot collaboration in assembly processes / Barravecchia, Federico; Bartolomei, Mirco; Mastrogiacomo, Luca; Franceschini, Fiorenzo. - ELETTRONICO. - 35:(2023), pp. 2-9. (Intervento presentato al convegno Italian Manufacturing Association Conference - XVI AITeM tenutosi a Napoli) [10.21741/9781644902714-1].

Availability:
This version is available at: 11583/2982329 since: 2023-09-20T09:10:34Z

Publisher:
Materials Research Forum LCC

Published
DOI:10.21741/9781644902714-1

A bio-inspired reinterpretation of symbiotic human-robot collaboration in assembly processes

Federico Barravecchia[a *], Mirco Bartolomei[b], Luca Mastrogiacomo[c] and Fiorenzo Franceschini[d]

Politecnico di Torino, DIGEP (Department of Management and Production Engineering), Torino, Italy

[a]federico.barracchia@polito.it, [b]mirco.bartolomei@polito.it, [c]luca.mastrogiacomo@polito.it, [d]fiorenzo.franceschini@polito.it

Keywords: Human-Robot Collaboration, Robotics, Bio-Inspired

Abstract. The emergence of collaborative robotics allowed humans and robots to work closely together to perform manufacturing activities. By combining their distinctive strengths and abilities, humans and robots can support each other in completing complex tasks. The relationship between humans and robots is frequently described in the literature as symbiotic. However, the concept of symbiosis, originally conceived in natural science, is often oversimplified as the mere exchange of mutual benefits. In practice, the term 'symbiosis' encompasses a wide range of interactions, ranging from relationships with positive impacts to relationships with negative impacts. Understanding the foundation of Human-Robot Symbiosis is crucial for its management. Two are the primary aims of this paper: (i) reinterpreting the collaborative tasks in assembly processes according to the properties of symbiotic relationships; (ii) proposing a novel approach for evaluating assembly tasks based on the bio-inspired features of symbiotic Human-Robot collaborative systems.

Introduction

Collaborative robotics refers to the integration of human operators and robots working together to achieve a common goal in manufacturing processes [1]. Unlike traditional robotics, which typically involves robots working independently and autonomously, collaborative robots (cobots) facilitate the active participation of human operators in the process [2,3]. This allows for combining the strengths and abilities of human operators and cobots to achieve greater efficiency, precision, and safety in tasks [4].

In the literature, several studies refer to Human-Robot Symbiosis as a type of collaboration in which humans and robots work together in a mutually beneficial relationship where respective strengths are exploited to improve the overall performance and efficiency of the system [5]. It is important to acknowledge that although symbiosis is expected to result in a mutually beneficial relationship, it encompasses positive and negative relationships where both parties can be negatively impacted. In the context of human-robot symbiosis, this means that while the collaboration may improve overall performance and efficiency, it can also lead to negative effects. In this consideration, a more nuanced understanding of the dynamics involved in Human-Robot Symbiosis can help avoid potential adverse outcomes and optimise the benefits.

In this consideration, this paper aims to present a novel bio-inspired perspective on Human-Robot Collaboration (HRC). By drawing parallels to the relationships between organisms in natural ecosystems, the study seeks to deepen our understanding of human-robot symbiosis. To accomplish this, the paper proposes a categorisation of potential symbiotic relationships between humans and robots, examining them in detail and identifying the elements of exchange (symbiotic factors) that shape the relationship. Additionally, the research introduces a practical evaluation method, which can be used to discern the nature of the specific relationships established in collaborative assembly tasks, thus, identifying areas of strength and weakness and opportunities for improvement.

Human-Robot interactions

Based on literature, a summary of possible human-robot interactions is presented below, listed in order of complexity [5–7]:

- *Coexistence/Autarky*: refers to case in which human and robot performs different task with different work goals, but they share the physical space.
- *Supervising*: in this type of interaction, the robot has limited autonomy and requires constant input and direction from the human operator. The tasks are performed simultaneously and towards the same goals, but the robot has limited independence, and adaptability is not a requirement.
- *Cooperation*: refers to the coordinated effort between humans and robots to achieve a common goal, with each party working on a specific task or set of tasks. In this sense, cooperation can be defined as a structured way of working together, where roles and responsibilities are clearly defined and there is a clear division of activities.
- *Supportive*: robots or humans can act in a supportive way, i.e. in a master-slave relationship. Despite the sharing of the objective, resources and workspace there is no autonomy in the decision of the task for the supporter.
- *Collaboration*: refers to a process where robots and humans share tasks, information, and resources to achieve a common goal. Operations are carried out simultaneously and in direct contact, the autonomy in carrying out operations is divided equally between the agents.
- *Symbiotic Collaboration*: in this kind of interaction human and robot are mutually dependent on each other, the robot and human work together in a complementary way.

Reinterpreting Human-Robot Symbiosis

This section provides an overview of the various types of symbiotic relationships that can be outlined between humans and robots within the context of symbiotic collaboration. The taxonomy aims to support the analysis and design of human-robot symbiotic relationships. The same symbiotic relationships found in nature can be used to categorise potential symbiotic relationships between humans and robots. These include six typologies: mutualism, commensalism, parasitism, amensalism, incompatibility and neutralism. Following this scheme, Figure 1.A outlines the framework of the possible Human-Robot symbiotic relationships. In detail, the symbiotic relationships are the following:

- *Mutualism*, it refers to a symbiotic relationship where both the human and the robot benefit from working together towards a common goal. In HRC, this relationship can occur when the robot performs repetitive and physically demanding tasks while the human worker focuses on tasks requiring cognitive skills. An example is in an assembly process where the robot's precision and speed in completing repetitive tasks increases overall efficiency, and the human's cognitive skills enhance quality control, resulting in a mutually beneficial outcome.
- *Commensalism*, it is a relationship between humans and robots where one agent benefits, while the other is neither helped nor harmed. An example is using a robot to lift and move heavy finished products at the end of an assembly process. This benefits the human by reducing workload and risk of injury, while the robot is not directly impacted positively or negatively by the human's presence.
- *Parasitism*, it refers to a symbiotic relationship where one agent benefits at the expense of the other. In the context of HRC, an example of human-robot parasitism could be when the

robot is assigned a task that a human worker can complete faster. This negatively impacts the robot's efficiency, while the human worker benefits by saving physical effort.

- *Amensalism*, it is a symbiotic relationship where one agent has a negative effect on the other without any benefit to itself. An example in HRC is when a robot emits high levels of noise or vibrations, interfering with the human worker's ability to communicate and hear warning signals, leading to an increased risk of accidents. The human worker is negatively impacted by the robot's presence, while the robot doesn't benefit from the human's presence.
- *Incompatibility*, it occurs when the human and robot are unable to work together effectively or safely. An example is during a robotised welding task, where the robot can pose a risk to the worker's safety by exposing them to the welding flame, while the presence of the human worker can also hinder the robot's movement and speed.
- *Neutralism*, it is a symbiotic relationship where both the human and robot coexist without impacting or affecting each other. This can occur when they are working on different tasks or in different areas and do not interact with each other. In such cases, the mutual impacts are negligible, and neither agent benefits nor is harmed by the presence of the other.

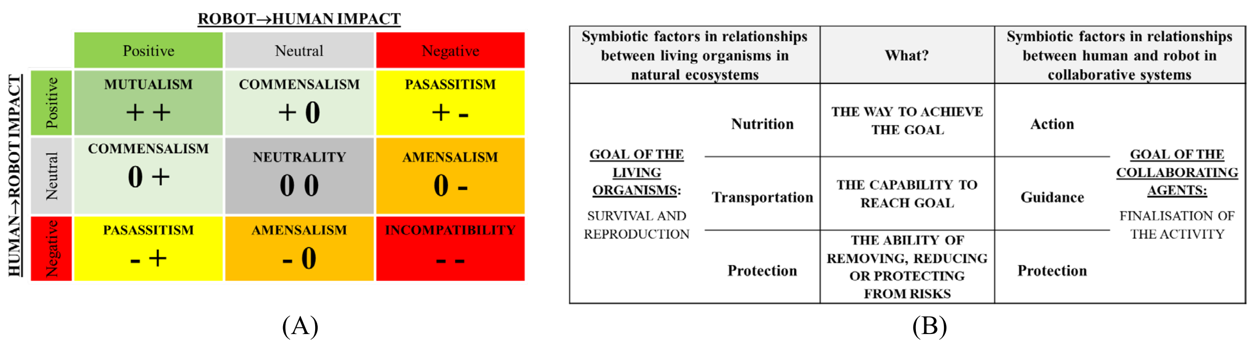


Fig. 1. (A) Classification of symbiotic human-robot relationships. Legenda: "+" positive impact of the relationship. "0" neutral impact of the relationship. "-" negative impact of the relationship. (B) Symbiotic factors in natural ecosystems and in collaborative systems.

Symbiotic relationships between living organisms are regulated by the exchange of symbiotic factors. To fully optimise human-robot symbiosis, it is necessary to identify the symbiotic factors exchanged between humans and robots and understand how they operate in the interaction. In order to identify human-robot symbiotic factors, we took a two-step approach. Firstly, we examined natural symbiotic relationships and then, through analogy, we identified the relevant symbiotic factors for HRC (see Figure 1.B).

Living organisms typically exchange nutrition, transportation and protection [8]. To find an analogy between natural symbiotic factors and human-robot symbiotic factors, we initially defined the objectives of the two types of symbioses. The symbiosis between living organisms aims to allow the survival and reproduction of natural organisms. On the other hand, the goal of the symbiotic relationship between collaborative agents (humans and robots) is to complete a task or an activity.

By analogy, considering the different objectives of the interaction, we identified the symbiotic factors between humans and robots as *action*, *guidance* and *protection*. Figure 1.B depicts the analogy process followed for the definition of the HRC symbiotic factors, which can be described as follows:

- *Action*, it refers to the process of doing or receiving the concrete actions that are necessary to complete a task. It encompasses the physical actions of the agents, such as grasping, moving, and manipulating objects.

Materials Research Proceedings 35 (2023) 2-9 https://doi.org/10.21741/9781644902714-1

- *Guidance*, it refers to the capability of an agent, whether human or robot, to lead the completion of an activity through understanding what needs to be done and sharing that knowledge with the other agent.
- *Protection*, it pertains to the ability of an agent to safeguard the other agent from any threats that may arise from the collaboration. This can include physical hazards, such as collision or malfunction, as well as ergonomic and psychological risks, such as repetitive stress injuries.

Evaluating symbiotic human-robot collaboration in assembly processes

This section introduces an evaluation tool designed to determine the nature of the relationship between humans and robots during collaborative processes. In detail, the proposed approach focuses on the analysis of existing collaborative processes.

The evaluation tool is based on the assessments of a team of experts who, after observing a collaborative task, assigns a rating to each symbiotic factor introduced in the previous sections. These factors (action, guidance and protection) are further detailed into specific dimensions to capture the distinguishing features of the symbiotic human-robot relationship.

In detail, the action factor is broken down into two dimensions:

- *Effort*: agents can provide the necessary effort to complete the task, or they can cause an increase in effort for the other agent.
- *Speed*: agents can speed up or slow down the execution of the task.

The guidance factor is divided into two specific aspects:

- *Knowledge*: agents can know and share the sequence of activities to be completed.
- *Decision-making*: agents can use their decision-making ability to choose which task to perform.

The protection factor is decomposed into the following dimensions:

- *Ergonomics*: the activity of one agent may affect the working conditions and ergonomics (physical and mental) of the other agent.
- *Safety*: agents can expose/protect the other agent from risks or threats

The evaluations focus on the individual elementary tasks of the assembly process. The team of experts uses the evaluation items listed in Table 1 to rate the mutual impact of the agents on each of these dimensions. The term impact is used here to refer to the effects or consequences the cobot has on human, and vice versa. The evaluations are expressed on a 7-level ordinal scale ranging from L1 (very negative impact) to L7 (very positive impact). The intermediate level (L4) represents the absence of impact on the dimension of analysis [9]

The combination of the partial impact ratings of the six dimensions allows for an assessment of the total impact of the relationship. The impact, whether it be from the robot to the human or vice versa, is determined by taking into account both the importance assigned to each dimension and the specific partial impacts within those dimensions.

To comprehensively evaluate the total impact of an agent on the other across all six dimensions, it is essential to adopt an effective aggregation method. One such approach may be the ME-MCDM (Multi Expert - Multi Criteria Decision Making) method [10–12]. The ME-MCDM method involves the use of max, min, and negation operators to combine linguistic information provided for non-equally important criteria [10,11]. According to the ME-MCDM method, the total impact (TI) can be calculated as follows [10,11]:

$$TI = \min_{k}[max(Neg(I_k), V_k)]. \tag{1}$$

Materials Research Proceedings 35 (2023) 2-9 https://doi.org/10.21741/9781644902714-1

Being:
k the dimension of analysis, V_k the partial impact related to the k-th dimension, I_k the importance of the k-th dimension, $Neg(I_k)$ the negation of I_k. $Neg(L_i) = L_{q-i+1}$ where q is the number of rating level, for instance $Neg(L_7) = L_1$, $Neg(L_6) = L_2$ and $Neg(L_1) = L_7$.

The underlying logic of this method is that while low-importance criteria should have only a minimal impact on the overall aggregated value, highly important determinants should significantly contribute to the definition of the aggregated evaluation.

Table 2 illustrates a fictitious example of how the ME-MCDM method is applied in practice.

Case study

A simple case study is described to illustrate the application of the methodology in a real-world scenario. The case study concerns the collaborative assembly of a mechanical component, as shown in Figure 2.A. The assembly process was conducted within a collaborative environment with the involvement of a UR3-Universal Robot Cobot (see Figure 2.B).

The assembly process was decomposed into six elementary tasks (see the first column in Table 3), and through the rating of the 6 dimensions of analysis (see Table 1), the impacts of the agent's activity on the counterpart were evaluated. In the presented analyses, the weight of each sub-dimension was considered as follows: *effort* and *speed* were rated as very important (L6), while the other dimensions, including *guidance*, *decision-making*, *ergonomics*, and *safety*, were rated as slightly important (L3). The simplicity of the assembly operation and the absence of significant risks for the operator led the team of experts to assign greater importance to the sub-dimensions of the action compared to the other.

As an example, let us consider elementary task 5, which involves fixing an oval flange to the base. During this task, the cobot holds the flange in position while the human worker tightens the screws. In this case, the team of experts rated the impact of the cobot on the human worker's effort and speed as moderately positive (L6), as the cobot secures the workpiece, freeing the human worker's hands to tighten screws more easily and rapidly. Furthermore, the impact of the cobot on the human worker's knowledge was rated as slightly positive (L5), as the cobot's clamping of the oval flange indicates the manner in which the task is to be executed, thus providing guidance to the human worker. The impact on the other dimensions of analysis was rated as neutral (L4). On the other hand, the impact of the human on the robot has been rated as very positive (L7) for effort and speed, since the cobot would not be able to perform the task autonomously. The impact on the other dimensions of analysis was rated as neutral (L4).

By utilising the ME-MCDM aggregation technique, the outcome reveals in elementary task 5 a mutualistic relationship between the human and the cobot, as indicated by the positive total impact (L5) score for both.

The comprehensive outcomes of the analysis and the combined impact values for each elementary task are reported in Table 3. The relationship map depicted in Figure 2.C supports the identification of the resulting symbiotic relationship between humans and robots.

The analysis provides a preliminary foundation for optimising the collaborative assembly process. As an example, Task 4 was found to exhibit a parasitic relationship in which the robot gained an advantage at the expense of the human worker. Specifically, the cobot leaves the task of placing the oval flange in the correct position to be performed by the human worker. This has a negative impact on the human worker. After analysing the relationship, the need to redesign the task has emerged. This redesign involves assigning the responsibility of the task to the robot, thereby reducing the workload for the human worker.

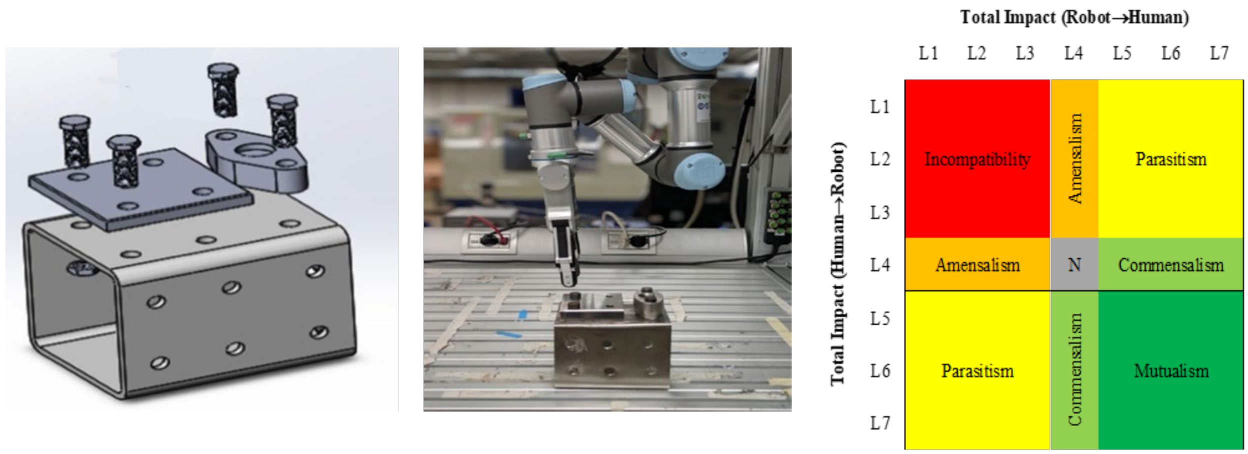
Tab. 1. Dimensions of analysis and rating scales.

Human-robot Symbiotic Factor		Dimensions of analysis and rating scales		
Action	Effort	The agent negatively contributes to required effort the task (L1)	The agent does not contributes to required effort the task (L4)	The agent positively contributes to required effort the task (L7)
	Speed	The agent significantly slow down the execution of the activity (L1)	The agent does not influence the time required to complete the task (L4)	The agent significantly speed up the execution of the activity (L7)
Guidance	Knowledge	The agent acts in ways inducing errors (L1)	The agent does not provide guidance on how to complete a task (L4)	The agent provides guidance on how to complete a task that the other agent alone would not be able to complete (L7)
	Decision-making	The agent applies an unsuccessful decision-making process (L1)	The agent does not carry out a decision-making process (L4)	The agent applies a successful decision-making process (L7)
Protection	Ergonomics	The agent significantly worsens the working conditions of the other agent (L1)	The agent does not influence the working conditions of the other agent (L4)	The agent significantly improves the working conditions of the other agent (L7)
	Safety	The agent significantly exposes the other agent to risk or threats (L1)	The agent does not influence the other agent's exposure to risks or threats (L4)	The agent significantly protects the other agent from risks or threats (L7)

Rating scale for each dimension: L1 L2 L3 L4 L5 L6 L7

Tab. 2. Application of the ME-MCDM method to a fictitious example (steps of the calculation).

Dimension (k)	**Effort**	**Speed**	**Knowledge**	**Decision-making**	**Ergonomics**	**Safety**
Importance (I_k)	L7	L4	L5	L5	L7	L7
Partial Impact (V_k)	L6	L2	L5	L4	L6	L4
$Neg(I_k)$	L1	L4	L3	L3	L1	L1
$max(Neg(I_k), V_k)$	L6	L4	L5	L4	L6	L4
Total Impact $\min_k[max(Neg(I_k), V_k)]$			L4			



(A) (B) (C)

Fig. 2. (A) Scheme of the assembled mechanical equipment. (B) Snapshot of collaborative robot UR3e during the assembly process. (C) Relationship map. "N" refers to the relationship of neutralism.

List of elementary tasks	Allocation	Robot → Human						Human → Robot						Human → Robot Total impact	Robot → Human Total impact	Relationship
		Effort	Speed	Knowledge	Decision making	Ergonomics	Safety	Effort	Speed	Knowledge	Decision making	Ergonomics	Safety			
1. Placement of the base in the working area.	R	L7	L5	L5	L4	L6	L4	L4	L4	L4	L4	L4	L4	L5	L4	**C**
2: Placement of the square flange on the base.	R	L6	L5	L5	L4	L6	L4	L4	L4	L4	L4	L4	L4	L5	L4	**C**
3: Fixing the square flange to the base with a pair of screws and nuts.	H	L6	L6	L5	L4	L4	L4	L7	L7	L4	L4	L4	L4	L5	L5	**M**
4: Placement of the oval flange on the base.	H	L3	L3	L4	L4	L4	L4	L5	L5	L5	L4	L4	L4	L3	L5	**P**
5: Fixing the oval flange to the base with a pair of screws and nuts.	H	L6	L6	L5	L4	L4	L4	L7	L7	L4	L4	L4	L4	L5	L5	**M**
6: Placement of the assembled component in another working area.	R	L7	L7	L4	L4	L7	L4	L4	L4	L4	L4	L4	L4	L5	L4	**C**

Tab. 3. List of elementary task and outcomes of the evaluation method. Allocation: H=human, C=cobot. Relationships: C=commensalism, M=Mutualism, P= Parasitism.

Conclusions

This article aims to provide a new perspective on Human-Robot Collaboration (HRC) by proposing a bio-inspired taxonomy of symbiotic relationships between humans and robots. The study identifies six different types of relationships depending on the type of impact generated by the robot on the human and vice versa. The proposed taxonomy can help to provide a comprehensive understanding of the nature of the interaction between humans and robots and provide a foundation for designing, evaluating, and improving HRC systems.

To apply the proposed perspective, an evaluation method to analyse the elementary tasks of an assembly process to identify relationships between humans and robots has been developed. The method enables the identification of potential areas for improvement, leading to optimised and enhanced HRC.

The proposed framework presents some limitations, as it only considers direct interactions and overlooks the broader organizational context. Additionally, the evaluation tool provides a static representation of relationships without accounting for their evolution over time or potential skill loss.

Regarding the future, our aim is to further develop and refine our approach, with the goal of incorporating it into early design activities for HRC systems. The proposed perspective on Human-Robot Symbiosis could provide valuable insights for designers to develop effective and efficient HRC processes in manufacturing contexts.

References

[1] Z.M. Bi, M. Luo, Z. Miao, B. Zhang, W.J. Zhang, L. Wang, Safety assurance mechanisms of collaborative robotic systems in manufacturing, Robot Comput Integr Manuf. 67 (2021). https://doi.org/10.1016/j.rcim.2020.102022

[2] V. Villani, F. Pini, F. Leali, C. Secchi, Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications, Mechatronics. 55 (2018). https://doi.org/10.1016/j.mechatronics.2018.02.009

[3] R. Gervasi, F. Barravecchia, L. Mastrogiacomo, F. Franceschini, Applications of affective computing in human-robot interaction: State-of-art and challenges for manufacturing, Proc Inst Mech Eng B J Eng Manuf. (2022). https://doi.org/10.1177/09544054221121888

[4] F. Barravecchia, L. Mastrogiacomo, F. Franceschini, A general cost model to assess the implementation of collaborative robots in assembly processes, International Journal of Advanced Manufacturing Technology. (2023). https://doi.org/10.1007/s00170-023-10942-z

[5] L. Wang, R. Gao, J. Váncza, J. Krüger, X. V. Wang, S. Makris, G. Chryssolouris, Symbiotic human-robot collaborative assembly, CIRP Annals. 68 (2019). https://doi.org/10.1016/j.cirp.2019.05.002

[6] S. El Zaatari, M. Marei, W. Li, Z. Usman, Cobot programming for collaborative industrial tasks: An overview, Rob Auton Syst. 116 (2019). https://doi.org/10.1016/j.robot.2019.03.003

[7] R. Müller, M. Vette, O. Mailahn, Process-oriented Task Assignment for Assembly Processes with Human-robot Interaction, in: Procedia CIRP, 2016. https://doi.org/10.1016/j.procir.2016.02.080

[8] M. Begon, C.R. Townsend, J.L. Harper, Ecology: From Individuals to Ecosystems, 4th Edition, Blackwell Publishing. (2005).

[9] F. Franceschini, M. Galetto, D. Maisano, Management for Professionals Designing Performance Measurement Systems, n.d. http://www.springer.com/series/10101

[10] R.R. Yager, Non-numeric multi-criteria multi-person decision making, Group Decis Negot. 2 (1993). https://doi.org/10.1007/BF01384404

[11] R.R. Yager, An approach to ordinal decision making, International Journal of Approximate Reasoning. 12 (1995). https://doi.org/10.1016/0888-613X(94)00035-2

[12] F. Barravecchia, L. Mastrogiacomo, F. Franceschini, The player-interface method: a structured approach to support product-service systems concept generation, Journal of Engineering Design. 31 (2020). https://doi.org/10.1080/09544828.2020.1743822