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Proto-Arch: Guidance Tool for Prototyping of Mechanical Systems at the Embodiment Design Phase

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Abstract
Prototypes are a critical aid in the product development process, allowing designers translate concepts to reality. However, the execution of prototypes depends heavily on the designer experience, evidenced in research in the need of creating design support tools to establish a standard for a prototyping effort. To improve on these findings, the Proto-Arch is introduced as a partial result of creating a standard for executing prototypes in each product development phase based on the prototyping roles and purposes. Proto-Arch defines the prototyping activities in the embodiment design phase.

Keywords: prototyping, embodiment design, product development, design tools, design methods

1. Introduction

Product design is becoming more demanding due to the constant evolution of trends and necessities of the market, creating smaller gaps for innovation, and generating significant impact on the end user, while being efficient in terms of time and resources. To support this development process, prototypes are essential tools to generate, describe, analyse, and test the system being designed (Jensen et al., 2016). Prototypes have many definitions, according to Ulrich *et al.* (2020) they are *"an approximation of the product along one or more dimensions of interest"*, Lauff *et al.* (2018) define them as a *"physical or digital embodiment of critical elements of the intended design, and an iterative tool to enhance communication, enable learning, and inform decision-making at any point in the design process"*. Prototypes are artifacts that approximate a feature or requirement of the final product service or system (Otto and Wood, 2001). Prototypes on the *"engineering"* domain focus on the creation of the product, being the outcomes of the processes and tools available to the design team to help to move from concept to reality (Christie *et al.*, 2012).
Literature shows that the effectiveness of prototyping depends on the designers' experience, driven by intuition, and how they apply design knowledge and manage resources and processes (Schork and Kirchner, 2018). This is mainly evidenced in the academic field; where research has shown that engineering students have a vague concept of prototypes in terms of their scope compared to their professional counterpart (Lauff *et al.*, 2017). However, experience does not entirely eliminate uncertainties regarding the influential variables and properties when executing a prototype, which are particularly helpful when the level of innovation is high with multiple unknown factors. Therefore, it is important to propose tools and methods in how to approach the prototyping practice. This study presents the Proto-Arch as a guidance tool for the prototyping analysis of mechanical systems in the embodiment design phase of the product development process, to help the designer to better understand and differentiate the needs for their protype throughout this design phase, starting from the architecture (component, subsystem, or system level) of the prototyping intent, to obtain a route of applicable

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executions; trying to close a possible gap of knowledge and experience by leaving out all the prototyping effort factors to the designer's consideration.
This paper is presented with the following structure. Section 2 presents a literature review from which the Proto-Arch is based on, Section 3 explains the structure of the tool, an example of using the Proto-Arch is presented in Section 4, finally Section 5 extends the conclusions and future work.

2. Related work

Bibliography evidences the existence of different tools to support prototyping activities. Christie et al. (2012). presents a list of 9 factors to determine a strategy for engineering prototypes, translated to a series of 13 question to establish a prototyping strategy. Dunlap et al. (2014), and Camburn *et al.* (2015); proposed a series of heuristics based on 6 prototyping techniques, each with a series of Likert-scale questions to stablish the prototyping strategy; followed by a review of different prototyping design methods where they elaborate on each of the 6 techniques (Camburn *et al.*, 2017). Menold *et al.* (2017) presented the *Prototype for X* as a framework for structuring prototyping activities incorporating a human design centred design aspect. As a continuation to this framework Lauff *et al.* (2019) introduced the *Prototyping Canvas* a planning tool to answer critical questions about the intended design and create the most basic version of a prototype. A common characteristic of these studies is the way they propose the strategy, by not establishing a specific order for the considerations and questions they present. To define a prototyping activity, there should be dependence between questions and a sequence that makes the definition of the prototyping clearer for the user who executes it.
Hansen *et al.* (2020) argued that the existing prototyping support are focused on how to establish prototyping as a specific activity, but don't consider that prototyping should be considered as a process. Then, they present the *Prototyping Planner* as a support tool that considers the purpose of the prototypes and a list of activities needed in the design process, defining four steps: think, build, expose, and act. Further, the authors introduced the *Prototyping Target* (Hansen *et al.*, 2021) to plan what to prototype during the design process, as a complement to the *Prototyping Planner*.
Authors agree that prototyping is an activity that should be considered throughout the product development process, and, a prototyping tool should be oriented towards the product design phases, where a series of questions are presented according to the deliverables of each phase. These tools should be presented to make decisions, guiding, or planning the prototyping exercise. In addition, they need to avoid open-ended questions, which is something recurrent in the mentioned studies since they leave to the user's consideration the definitions of key variables to establish what and how to prototype.

3. Proto-Arch

This section presents the Proto-Arch, a design support tool to define how to execute prototyping activities for a design problem in the embodiment design phase of the product development process. Proto-Arch merges different aspects and variables found in literature about prototype execution, presented in a series of lineal questions, divided in 5 main blocks, which are focused on the roles and purposes of the prototypes to meet the objectives of the embodiment design phase.

3.1. Product design phases - Prototyping roles and purposes

The inputs and outputs for each product development phase have been considered to establish the prototyping activities, as it is presented in the (Table 1). Pahl and Beitz (1996) expose that the product development process is defined within the phases of planning and task clarification, conceptual design, embodiment design and detail design. Phases of manufacturing, testing and delivery have been also considered.
This is followed by finding the roles and purposes of prototypes. Menold et al. (2017) in the Prototype for X state that prototypes should answer critical questions for project success with the purposes of feasibility, viability, and desirability, which are also proposed in the Prototyping Planner (Hansen *et al.* 2020) based on the prototyping roles of exploration, evaluation, and communication. This study uses the taxonomical classification of the roles and purposes of prototypes proposed by Petrakis *et al.* (2019) shown in (Table 2), useful to make the connection between product development phases and the purposes of prototypes.

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Table 1. Product design process phases

ITEM	Product development phase	Input	Output
A	Planning and task clarification	Task, market, environment	Requirement list
B	Conceptual design	Requirement list	Principle solution
C	Embodiment design	Principle solution	Product definitive layout
D	Detail design	Product definitive layout	Product documentation
E	Manufacture	Product documentation	Alpha product
F	Testing	Alpha product	Tested Product
G	Delivery	Tested product	User product

Table 2. Prototyping roles and purposes Petrakis et al. (2021)

Exploration and requirement elicitation	
1	Engage with prototypes in order to understand and define the design problem in depth.
	Stimulate user interaction with early prototypes in order to:
2	Uncover unknown user requirements
3	Prioritise user requirements
4	Identify exact target user groups.
5	Enhance ideation with the aim of generating a wider range of concepts (divergence).
6	Evaluate multiple concepts by comparing them and informing concept selection (convergence).
7	Compare the concept's characteristics and performance to existing competitor products
Learning	
8	Answer questions regarding the product's functionality and technical aspects
9	Answer questions regarding the users' requirements, preferences, and behaviours.
10	Answer questions regarding manufacturing concerns such as cost, tooling, and materials.
11	Assess feasibility of the concept and verify its practical potential through a proof of concept.
12	Reveal unknown information about factors that may affect performance.
Project Planning	
13	Set deadlines and milestones in order to manage the design process in terms of time.
14	Establish forward progress by ensuring the concept has reached a desired degree of functionality and move project through the next phases.
Communication	
15	Explain concept to stakeholders by demonstrating how it functions.
16	Communicate the concept's aesthetics and look-and-feel features.
17	Visualise spatial features in order to understand concept in 3D.
18	Use prototype as a representation and persuasion tool in design meetings or critique presentations
	Get feedback in relation to functionality or aesthetics from:
19	Users
20	Focus group
21	Expertise/company
Design refinement	
22	Identify and optimise key performance features.
23	Reveal and decrease fabrication errors.
24	Understand limitations and define margins of improving the concept.
	Test concept and gather experimental data in relation to:
25	Functionality, through testing performance.
26	User requirements, through user testing.
27	Validate the product's technical specifications and user requirements.
System integration	
28	Ensure compatibility of the concept's parts and subsystems.
29	Evaluate aesthetics of the concept's assembly.
30	Configure functionality of the concept's assembly.

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(Table 3) presents the selected prototyping purposes for each product development phase, being the embodiment design phase the one with the highest number (16) of applicable purposes for the fulfilment of its objective, from which the development of the Proto-Arch is derived.

Table 3. Product design phases and prototyping purposes

Product development phase	Prototyping purpose
Planning and task clarification	2, 4, 13, 18
Conceptual design	1, 3, 5, 6, 7, 8, 9, 15, 16, 17, 29
Embodiment design	1, 6, 8, 11, 12, 13, 15, 17, 20, 21, 22, 24, 25, 27, 28, 30
Detail design	10
Manufacture	10, 23
Testing	12, 19, 20, 25, 26, 27
Delivery	N/A

3.2. Proto-Arch structure

The format of the tool is presented with similarities; first, to the *Prototyping Canvas* regarding the objective of the prototype (*assumptions and questions* block) available resources (*resources to build* block), and prototyping methods (*prototyping approaches* block). Second, with the *Prototyping Planner* within the *Frame* step, in the *Focus* section, to specify what it is going to be prototyped, and within the *Build* step, in the *What to Build* and *Build Plan* sections, to stablish the fidelity of the prototype and to define how the designer is going to conceive the prototype. These similitudes can be found in the *Proto-Arch* in Blocks 1, 2 and 5. Additionally, the one-page sheet format is used, following the recommendation mentioned in the literature of prototyping tools, of being simple and having a general scope of critical information about the prototyping effort. (Figure 1) shows the general scheme of the Proto-Arch.

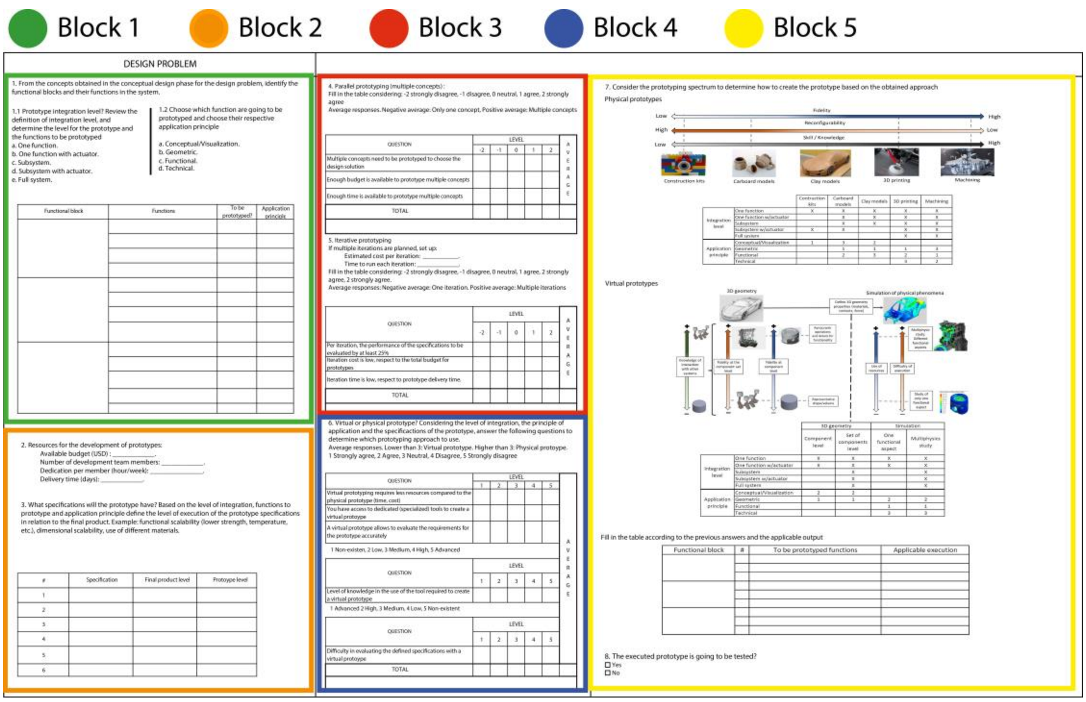

Figure 1. Proto-arch structure

- **Functional block - Level of integration - Principle of application (Block 1):** According to the design problem and the possible solutions concepts obtained from the conceptual design phase, first, the designer is asked to identify the functional blocks and their respective functions. These functional blocks in the Proto-Arch refer to a component or group of components within the system; not to be mistaken with the functional block from the transparent box. Then, the designer

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determines the integration level for the intended prototype, followed by choosing which functions the prototype must represent and their respective application principle (Canuto da Silva and Kaminski, 2015). The definitions for the integration level and application principle are shown in (Table 4).

Table 4. Level of integration and principle of application definitions

Level of integration	**Single function:** Representation of a specific function of the system without considering its actuation. **Single function with actuator:** Representation of a specific function of the system considering its actuation. **Subsystem:** Representation of a set (2 or more) of functions of the system without considering their actuation. **Subsystem with actuator:** Representation of a set (2 or more) of functions of the system considering their actuation. **Full system:** Prototype showing all system functions executable.
Principle of application	**Conceptual/Visualization:** Evaluate prototype appearance. **Geometric:** Evaluate prototype's geometry, fit and interferences. **Functional:** Evaluate the performance of the prototype. **Technical:** Evaluate the manufacturing or pilot test of the prototype.

- **Resources - Specification level (Block 2):** The designer is prompted to input the resources available for the prototyping activities, considering the budget available for the design problem, number of team members, the dedication of each member measured in hours per week, and the number of days to deliver the prototype. Then, the designer is asked for the level of execution of the prototype in comparison to the final product. Schork and Kirchner (2018) present that such execution must consider the superordinate requirements related to the available resources; and the particular requirements that depend on the requirements of the final product, where the designer determines what is intended to be prototyped, either using totally or partially requirements. For the Proto-Arch, the term requirement is replaced by specifications, since we consider that it is more accurate to consider engineering terms and measurable variables on how the final product and the prototype will be executed. These specifications are translated from the "to be prototyped" functions according to their application principle, and the designer determines their level for the final product and for the prototype.
- **Parallel prototyping - Iterative prototyping (Block 3):** This section presents the designer with two sets of questions regarding the possibility of prototyping multiple concepts and whether to do it iteratively. Both sets use some of the heuristics and the same evaluation method proposed by Camburn et al. (2015), where it is stated that when a neutral result is obtained, the user should change the original answers until getting a result towards one option, which should also be done in the Proto-Arch. In the case of iterative prototyping, prior to answering the questions, an estimate of costs and development time for one iteration of the concept is requested, considering the input of available resources.
- **Virtual prototyping - Physical prototyping (Block 4):** Five heuristics are presented regarding the two great dimensions of executing a prototype: virtual or physical. To establish which dimension is more favourable for the prototyping activity, these heuristics are evaluated from 1 to 5, with three different scales. In case of getting a neutral result in the total evaluation, the answers should be reconsidered.
- **Prototyping techniques spectrum (Block 5):** The last section of the tool presents the spectrum of the physical (Mathias *et al.*, 2019) and virtual prototyping techniques. Each spectrum is accompanied by an auxiliary table, that indicates, according to the integration level, which techniques are recommended to be used and their priority depending on the application principle. These spectrums are meant to be used for the designer as a guide to define the applicable execution for each of the "to be prototyped" functions. Finally, the designer is inquired if the proposed prototype after its execution must proceed to a testing phase with a Yes/No question.

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From the total of the 16 applicable prototyping purposes for the embodiment design phase, 11 are within the current state of the tool and are distributed as follows: Block 1 (8, 27), Block 2 (8, 13, 22, 24, 28, 30), Block 3 (1), Block 4 (27) and Block 5 (15, 17, 28, 30). The 5 remaining purposes (11, 12, 20, 21, 25) are focused towards testing the built prototype and getting feedback, which are pending to be included.
Compared to the prototyping tools found in the literature, the *Proto-Arch* addresses the inquiries about the prototype intent avoiding open-ended questions. Block 1 aids the designer to determine the objective of the prototype by choosing the functions that must be met based on the integration level and application principle. Block 2 makes the designer to translate the functions into specifications and states their execution level, for the final product and for the prototype as an initial guide of how the prototype should be built. Blocks 3 and 4 integrate the heuristics of different prototyping approaches adding the consideration of the level of the specifications for the prototype. Finally, Block 5 presents a proposal of different applicable executions of the prototype within the virtual and physical spectrum, determined by the previously answered questions.

4. Case study

This version of the *Proto-Arch* is the result of an early testing phase carried out with a group of 4 MSc students on how to use the tool and how the information is presented within the five blocks. These changes are presented as prompts for the user to specify the functions of the design and which ones are going to be prototyped, to define the level of the specifications for the prototype and their integration level, to apply a modified version of the heuristics about prototyping approaches found in literature, and, finally, to execute the applicable proposal.
The case study focuses on presenting how the Proto-Arch works on the design problem for the electrification of an outboard engine; being the prototyping effort the splice interface between the outboard engine and the gear box, represented as the green contour in the transparent box of the (Figure 2).

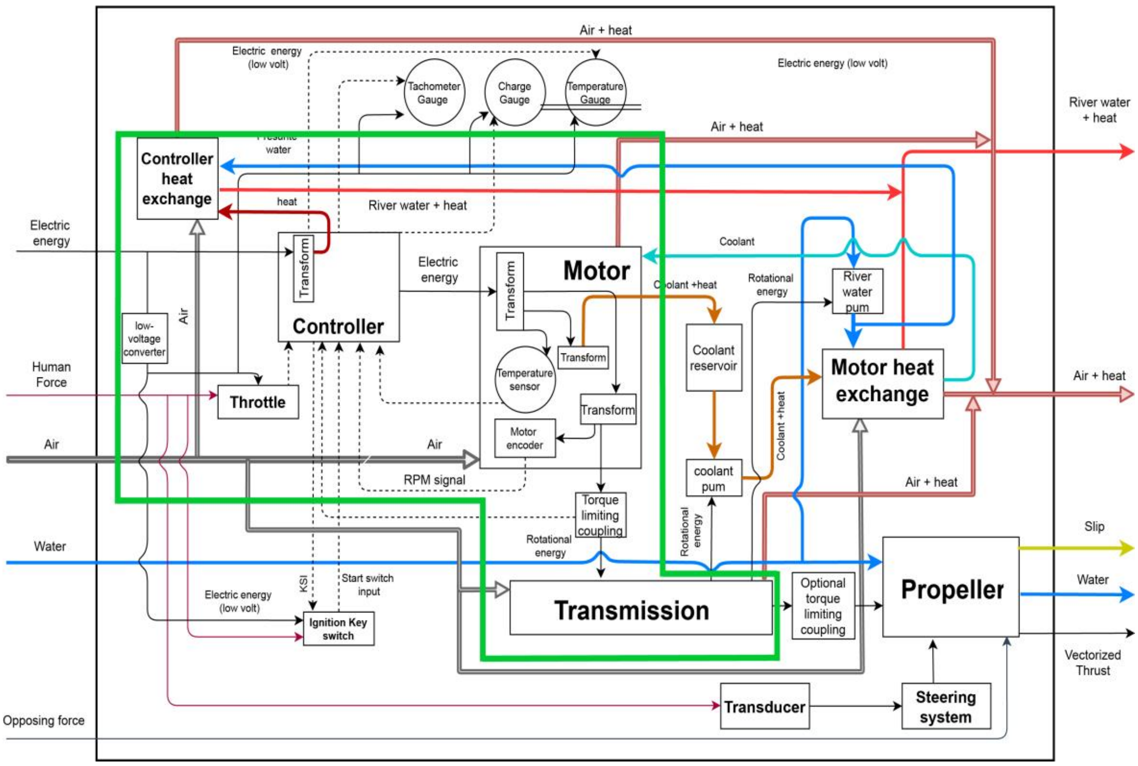

Figure 2. Outboard engine transparent box

In Block 1 (Figure 3) of the Proto-Arch the user defines 3 main components of the interface with their respective functions and application principle. "Subsystem" is the chosen integration level due to having multiple functions for the prototype.

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1. From the concepts obtained in the conceptual design phase for the design problem, identify the functional blocks and their functions in the system.

1.1 Prototype integration level? Review the definition of integration level, and determine the level for the prototype and the functions to be prototyped

a. One function.
b. One function with actuator.
c. Subsystem.
d. Subsystem with actuator.
e. Full system.

1.2 Choose which function are going to be prototyped and choose their respective application principle

a. Conceptual/Visualization
b. Geometric.
c. Functional.
d. Technical.

Functional block	#	Functions	To be prototyped?	Application principle
Lower frame	1	Bearing surface of drive components		
	2	Create alignment between output shaft and drive shaft	X	Geometric
	3	Mechanical joint interface between gearbox and original engine exhaust gasket	X	Geometric
	4	Withstand radial loads transmitted by shaft support bearings; and generate stress flow to original motor housing	X	Functional
Turrets	5	Create clearance height between lower and upper frame	X	Geometric
	6	Provide structural support to upper frame	X	Functional
	7	Mechanical interface for stress transfer between upper and lower frame	X	Functional
	8	Generate alignment of components to ensure design clearances	X	Geometric
Upper frame	9	Withstand gearbox main propeller	X	Functional
	10	Reference surface for the assembly of components and accesories external to the system		
	11	Bearing surface of drive components		
	12	Create alignment between output shaft and drive shaft	X	Geometric
	13	Withstand radial loads transmitted by shaft support bearings; and generate stress flow to original motor housing	X	Functional
	14	Generate guiding surface to enable tensor shaft displacement	X	Functional

Figure 3. Proto-arch applied block 1

This is followed by establishing the available resources for the prototyping activities and defining the specifications for the 11 selected "To be prototyped" functions as presented in Block 2 (Figure 4). From the total specifications only one (#2) has the execution level for the prototype equal to the final product.

2. Resources for the development of prototypes:
Available budget (USD) : 3.000.
Number of development team members: 3.
Dedication per member (hour/week): 40.
Delivery time (days): 180.

3. What specifications will the prototype have? Based on the level of integration, functions to prototype and application principle define the level of execution of the prototype specifications in relation to the final product. Example: functional scalability (lower strength, temperature, etc.),

#	Specification	Final product level	Prototype level
2	Distance between contours	+/- 0,1 mm	+/- 0,1 mm
3	Centre-to-centre distance between holes for fasteners	+/- 0,02 mm	+/- 0,1 mm
4	Maximum Von Mises stress	80 MPa	50 MPa
5	Turret height deviation	+/- 0,01 mm	+/- 0.5 mm
6	Maximum applicable load	80 KN	60 KN
7	Maximum Von Mises stress	80 MPa	50 MPa
8	Tolerance in register pin location dimensions (x,y)	+/- 0,1 mm	+/- 1 mm
9	Maximum applicable load	55 KN	40 KN
12	Rod centerline spacing	+/- 0,5 mm	+/- 1 mm
13	Maximum applicable load	8 KN	4 KN
14	Slot faces roughness	0,75 μm	2,2 μm

Figure 4. Proto-arch applied block 2

Then the user is inquired to determine parallel and iterative prototyping for the design problem (Figure 5), where it's suggested for the prototyping activity to prototype one concept and one iteration.

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4. Parallel prototyping (multiple concepts)
Fill in the table considering: -2 strongly disagree, -1 disagree, 0 neutral, 1 agree, 2 strongly agree.
Average responses. Negative average: Only one concept, Positive average:

QUESTION	LEVEL -2	-1	0	1	2	AVERAGE
"To be prototyped" functional blocks have multiple execution routes	X					
Enough budget is available to prototype multiple concepts	X					
Enough time is available to prototype multiple concepts		X				
TOTAL	-4	-1	0	0	0	-1,667
Prototype only one concept						

5. Iterative prototyping
If multiple iterations are planned, set up:
Estimated cost per iteration (USD): 1.600.
Time to run each iteration (days): 60.
Fill in the table considering: -2 strongly disagree, -1 disagree, 0 neutral, 1 agree, 2 strongly agree, 2 strongly agree. Average responses: Negative average: One iteration. Positive average: Multiple iterations.

QUESTION	LEVEL -2	-1	0	1	2	AVERAGE
Per iteration, the performance of the specifications to be evaluated is improved by at least 25%.				X		
Iteration cost is low, respect to the total budget for prototypes		X				
Iteration time is low, respect to prototype delivery time.		X				
TOTAL	0	-2	0	1	0	-0,333
Prototype only one iteration						

Figure 5. Proto-arch applied block 3

Finally based on the "to be prototyped" functions and their specifications for the prototype level, it is proposed to create a virtual prototype (Figure 6). Filling out the heuristics for Block 3, the user obtained a neutral result in the *Iterative prototyping* item, and reviewing the answers decided to change the last heuristics from 0 to -1, with the total result that only one iteration should be prototyped.

6. Virtual or physical prototype? Considering the level of integration, the principle of application and the specificactions of the prototype, answer the following questions to determine which prototyping approach to use.
1 Strongly disagree, 2 Disagree, 3 Neutral, 4 Agree, 5 Strongly agree

QUESTION	LEVEL 1	2	3	4	5	AVERAGE
Virtual prototyping requires less resources than physical prototyping (time, cost).				X		
You have access to dedicated (specialized) tools to create a virtual prototype.				X		
A virtual prototype allows to evaluate the specifications for the prototype accurately.	X					
1 Nonexistent, 2 Low, 3 Medium, 4 High, 5 Advanced						
QUESTION	LEVEL 1	2	3	4	5	
Level of knowledge using the dedicated tool to create a virtual prototype.				X		
1 Advanced 2 High, 3 Medium, 4 Low, 5 Nonexistent						
QUESTION	LEVEL 1	2	3	4	5	
Difficulty in evaluating the defined specifications with a virtual prototype.			X			
TOTAL	1	0	3	12	0	3,2
Virtual prototype						

Figure 6. Proto-arch applied block 4

For the final Block 5, having a virtual prototype as the suggested dimension for creating the prototype the user inputs all the "to be prototyped" functions and selects the applicable execution for each, within the categories of 3D geometry or Simulation (Figure 7).

Functional block	#	To be prototyped functions	Applicable execution
Lower frame	2	Create alignment between output shaft and drive shaft	3D Geometry - Components set level (High fidelity)
	3	Mechanical joint interface between gearbox and original engine exhaust gasket	Simulation - One functional aspect
	4	Withstand radial loads transmitted by shaft support bearings; and generate stress flow to original motor housing	
Turrets	5	Create clearance height between lower and upper frame	3D Geometry - Components set level (High fidelity)
	6	Provide structural support to upper frame	Simulation - One functional aspect
	7	Mechanical interface for stress transfer between upper and lower frame	
	8	Generate alignment of components to ensure design clearances	3D Geometry - Components set level (High fidelity)
	9	Withstand gearbox main propeller	Simulation - One functional aspect
Upper frame	12	Create alignment between output shaft and drive shaft	3D Geometry - Components set level (High fidelity)
	13	Withstand radial loads transmitted by shaft support bearings; and generate stress flow to original motor housing	Simulation - One functional aspect
	14	Generate guiding surface to enable tensor shaft displacement	

8. Executed prototype is going to be tested?
☐ Yes
☐ No

Figure 7. Proto-arch applied block 5

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5. Conclusions & future work

The Proto-Arch is a tool to guide prototyping activities in the embodiment design phase of the product development process that establishes a throughout strategy for the execution of prototypes, using influential variables and factors in the design of prototypes found in research, primarily the prototyping roles of exploration and elicitation of requirements, learning, project planning, communication, design refinement and system integration and their respective purposes. Looking for to generate a prototyping cycle according to the moment in time for a project, it is noticed that the embodiment design phase presents the highest number (16) of applicable purposes to fulfil its objective, and thus, it is expected to present a higher dedicated effort towards generating prototypes compared to the other design phases. The introduced tool has close-ended questions and guidelines on how the user should fill out its 5 blocks, so, the tool establishes the prototype execution, instead of having open-ended questions that may influence the activity itself. The intended use of the Proto-Arch is for one specific moment in the embodiment design phase, therefore, if new information about the initial design problem is uncovered or added, the tool should be run through again, as it is not adaptable to these changes.

For future work multiple activities are planned. Initially, the Proto-Arch must be tested with larger sample to have a better perspective about its usefulness and consider potential modifications, such as looking for a different evaluation method for the heuristics in blocks 3 and 4, to avoid neutral results which make the user change the original responses. This will be followed by the creation of tools analogous to the Proto-Arch for the remaining product development phases. Finally, the remaining purposes that are not applied in the 5 main blocks would be integrated and used for defining a testing protocol for the prototypes in each product development phase.

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