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Conceptual Design Process of a Missile Model and Production Using Additive Manufacturing Method

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ABSTRACT

This study focuses on air-to-ground missile systems, which are widely used in Turkey and around the world and are becoming increasingly important. The development of missile systems takes into account various requirements defined by the end user. It is important to identify a system and its subcomponents that fully meet the requirements. This study analyzes an air-to-ground missile system and its main subcomponents identified through the conceptual design method based on the systematic design approach proposed by Pahl and Beitz. The aim is to determine the feasibility of obtaining an optimal solution that meets the requirements set by the conceptual design method. The missile design's optimal solution was modeled using SolidWorks software. A three-dimensional (3D) printer with FDM production technology was used to produce a prototype of the computer-modeled design. ABS and ABS-plastic blend filaments were preferred due to their material properties in the FDM production process. During the printing stage, the filament and output settings of the model were determined using the 3D printer's interface program. The filaments were then extruded through a nozzle, following the cross-sectional geometry of the part. The resulting model was printed in pieces and assembled with a tolerance of 0.1mm. This process resulted in a 3D model of the missile, which was created to represent the system structure in different colours. The study demonstrates that the conceptual design method can be used to develop innovative and meaningful missile models.

Keywords: Weapon system; 3D printer; Systematic design; Conceptual design

NOMENCLATURE

$E_{mechanical}$	: Mechanical energy
$E_{battery}$	: Battery energy
$E_{chemical}$	: Chemical energy
W_t	: Value from the tree of objectives
Σ_{ad}	: Sum of the weighted values
Σ_d	: Sum of values
ΣW_t	: Sum of values of the tree of objectives
Ø	: Diameter

1. INTRODUCTION

The defence industry is one of the important factors determining countries' power in the political and economic fields. In parallel with the technological advances in the world in the defence industry, there is a constant need for innovation, change and modernisation[1]. Accordingly, various research and development activities have been conducted, and new design methods are being studied[2].

By examining the already-developed design techniques, some deficiencies have been identified in classical methods, and several attempts have been made to correct these deficiencies. In this context, studies carried out during World War 2 gained importance in formulating the design process. This development continued in the following period, and design methods with new and more flexible representation techniques were emphasised. The most important researchers involved in the emergence of the current systematic design are Rodenacker, Roth, Koller, Pahl and Beitz, Kusiak, Ehrlenspiel and John[2].

There are various applications of the work of Pahl and Beitz in different fields. For instance, Koca and Mendi revealed the effect of the conceptual design approach in creating an optimum level of quality, time-saving and purpose-oriented quality product. In this context, a functional vest was designed for tour bicycle users, and up-to-date and original vest designs can be created with conceptual design[3]. Moreover, Erbulak and Erden[4] studied the decision of composite repair design using the Pahl and Beitz systematic design approach. Gürcüm and Üner[5] created a sample fabric collection using an exemplary textile design application based on the Pahl and Beitz model. Mayda and Börklü[6] proposed a model for Pahl and Beitz's conceptual design approach that includes quality function distribution and the theory of inventive problem-solving. To test the usability and reliability of this model, several researchers have conducted a sample water filter design application[6]. Additionally, some researchers developed a conceptual design process model based on the systematic design approach. The developed process model is a substructure for computer-aided conceptual design systems[7].

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Systematic design techniques can also be called modern design, which can classify the design process into scientific and formulatable processes without requiring the designer's personal experience or skill. As a result, the designer's cognitive, affective or dynamic input behaviour can be evaluated within the design process. Currently, computer technologies are also used in the evaluation phase of this design method[2].

Along with design methods, significant developments have been made in production methods and techniques. The most prominent of these developments is production technology with three-dimensional (3D) printers. 3D printing is the process of producing 3D solid objects from a 3D Computer-Aided Design (CAD) model prepared in a digital environment. The machines that perform these operations are called 3D printers. The 3D model prepared by the designer is divided into layers by slicing in the computer environment. These layers are printed so that the material melted during printing with the 3D printer overlaps each other and turns into concrete objects. 3D printer technologies work by stacking layers on top of each other[8].

3D printer technologies have made it possible to foresee problems that may occur in the product design and production process and solutions can be created. This also saves the designer time. Prototypes of CADs can be made with 3D printers. Compared with traditional methods, prototyping with 3D printers significantly reduces the process and cost, making a quick transition to mass production. Because of their advantages, 3D printers have been widely used in fields such as medicine, aerospace and defence[8].

When all these technological developments, current design and production techniques are examined, it is seen that creating a systematic way for weapon design and discovering new models and solutions have become a race today.

Inspired by these developments, this study focuses on the optimum solution for an air-to-surface missile system using the conceptual design method based on the systematic design approach proposed by Pahl and Beitz. Additive manufacturing technology was used in the production of this missile system. The missile model that creates the solution using a suitable 3D printer was produced using the Fused Deposition Modelling (FDM) method.

2. METHODOLOGY

In the systematic design method proposed by Pahl and Beitz, algorithmic ways are used regardless of the designer's abilities and creativity to create the design. Systematic design consists of sub-components, such as purpose clarification, conceptual design method, shaping and detailed design[9]. The conceptual design method is a method in which the optimum design solution is obtained by following some basic steps. These steps include determining and organising the design task (list of needs), general and basic expression of the task, creating function diagrams (structures), searching for working principles, combining (synthesis) working principles, selecting appropriate combinations, creating, showing and evaluating solution options[10]. Based on the above steps, the optimum solution was obtained, and the production of this solution was realised using an appropriate 3D printer technology.

3D printers vary in terms of technology used to produce objects, such as fused deposition modeling, stereolithography and selective laser sintering[11]. Among them, FDM or stacking by joining is the most well-known technique and has been used in this study[12].

The FDM manufacturing process involves extruding material through a nozzle that follows the cross-sectional geometry of the part. The model's material is a thin plastic wire-shaped filament[13]. This technique allows for the production of multi-part, moving mechanisms, and complex parts. Model materials such as acrylonitrile butadiene styrene (ABS), polyamide, polycarbonate, polyethylene, and polypropylene can be used. In this study, filaments with ABS and ABS-plastic mixture were preferred for producing the missile model based on their material properties.

3. MISSILE CONCEPTUAL DESIGN

The systematic design approach developed by Pahl and Beitz and the associated conceptual design method can easily be applied to all weapon systems when considering the issue of weapon systems design. However, the scope of this study has been narrowed by selecting missile systems from among the subjects with limited application areas, such as weapon systems, and conceptual design application has been made for these systems.

The structure of missiles differs according to the guidance systems they use. The parts that comprise the basic structure include the target seeker, warhead, guidance and control system, propulsion system, and control and stabilisation wings[14]. Within the scope of the study, the design steps were created based on this basic structure.

3.1 Determination and Organisation of Design Tasks

The first application in determining the design tasks is to determine the needs and desires necessary for the missile design. Needs are essential features. Based on the basic characteristics of a missile, the main headings for the needs include range, combat vehicle to be installed using the missile, target, cost, suitability for the platform to be fired and security. These identified headings and their subheadings are placed in a design specification, as shown in Table 1.

3.2 Abstraction and Problem Formulation

In the design of the missile, a problem definition is established according to the design specification. The general problem definition is that the missile reaches its target through the specified direction using the guidance system and the movement provided by the propulsion system.

3.3 Developing Functional Structures

According to the general definition of the problem, the entire functional structure suitable for the working system of a missile was developed. In the entire function, the inputs were determined as a signal, battery energy ($E_{battery}$) and chemical energy ($E_{chemical}$) and the outputs as mechanical energy ($E_{mechanical}$). The entire function structure expresses the operation-relationship logic of the design problem in a simple and understandable way.

Table 1. Missile design specification[2]

Missile design specification

Modifications	N/a	Needs	Supervisor
	N	1. The range of the missile should be as follows: - Short-Range (1000 km and less) - Mid-Range (between 1000 and 3000 km) - Intercontinental (minimum 5500 km) - Submarine launched (minimum 5500 km/3000 nautical miles)	
	N	2. The combat vehicle on which the missile will be mounted should be specified as follows: - Aircraft - Fixed ground platform - Movable ground platform - Attack helicopter - Unmanned Aerial Vehicle (UAV) - Marine platform	
	N	3. The target at which the missile will be fired must be specified as follows: - Ground targets - Marine targets - Light armed vehicles - Unarmored vehicles - Aircrafts - UAV	
	N	4. In the budget to be allocated to the missile, the parts to be given importance should be specified as follows: - Target seeker - Warhead - Guidance system - Propulsion (engine) system - Material specifications	
	N	5. The structure of the missile must be in mounting dimensions appropriate to the platform on which the shot will be made.	
	N	6. The missile system must be able to operate without harming the user.	

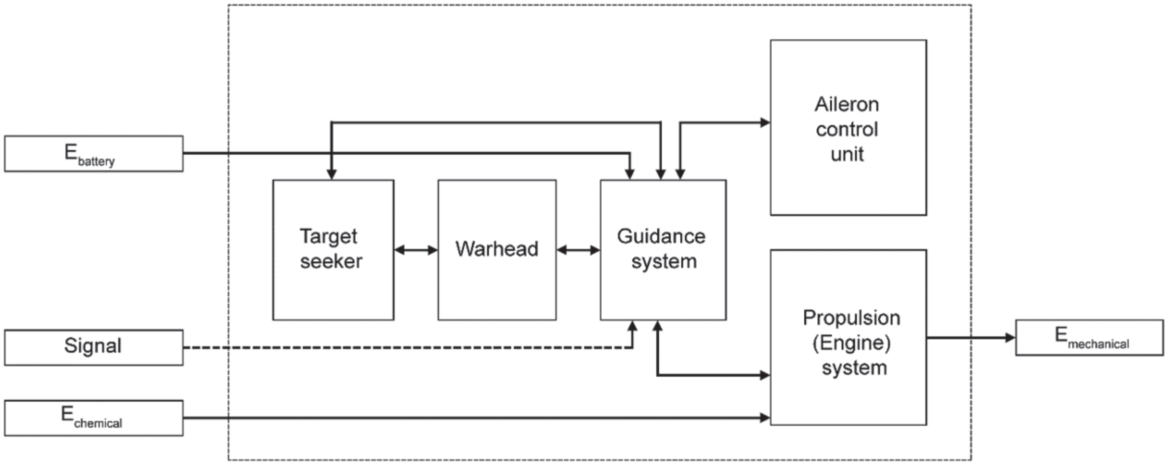


Figure 1. Sub-functional structure of the missile[2].

In the overall functional structure, the target seeker, warhead, guidance system, aileron control unit and propulsion (engine) system, which constitute the main parts of a missile system, are designated as sub-functions[15]. Figure 1 shows the sub-functions, which depend on the entire function and how they relate to each other.

3.4 Working Principle Search

Table 2 shows the basic solutions of the sub-function in the missile design by selecting the components according to the specific characteristics required in the design. Depending on the design and designer, the components in question can be specified differently. The solution/sub-function scheme created

Table 2. Missile design classification chart[2]

Solution / Sub-functions		1	2	3	4	5	6	7
1	Target seeker	Infrared imaging seeker (iir)	Semi-active laser seeker	No seeker				
2	Warhead	High explosive pressure particle effect	Sequential drill	Armour piercing	Incendiary extractor	Personnel	Tandem	High explosion anti-tank (heat)
3	Guidance system	Integrated inertial navigation system (ins)	Global positioning system (gps)	Earth referenced navigation system (erns)	Terminal guidance	Laser guidance		
4	Aileron control unit	Wingless	Fixed wing	Movable wings				
5	Propulsion (engine) system	Composite fuel	Solid fuel	Liquid fuel	Hybrid (solid + liquid) fuel	Electro–thermal (arcjeti resisto-jet)		

plays a crucial role in achieving the optimum solution in the design for the next stages.

3.5 Combining Solution Principles

The total number of solution options included in the missile design classification scheme can be calculated as 3×7×5×3×5=1575. Among these solution options, those that do not comply with the design specification, problem definition and general function structure were eliminated, and eight suitable solutions were determined using the systematic

Table 3. List of priority solutions15

List of priority solutions	
Solution 1	1.3–2.1–3.1, 3.2, 3.3–4.2, 4.3–5.1
Solution 2	1.1–2.1–3.1, 3.2, 3.3–4.2, 4.3–5.1
Solution 3	1.1–2.2–3.1, 3.2, 3.3–4.2, 4.3–5.1
Solution 4	1.1–2.3–3.1, 3.2, 3.3–4.2, 4.3–5.1
Solution 5	1.2–2.1, 2.3, 2.4, 2.5–3.4–4.2,4.3–5.1
Solution 6	1.1–2.1–3.1, 3.4–4.2, 4.3–5.4
Solution 7	1.1–2.6–3.5–4.2, 4.3–5.1
Solution 8	1.1–2.7–3.5–4.2–5.2

Table 4. Selection card[2]

Missile selection card

Solution variants		A	B	C	D	E	F	G	Opinions (reasons)	Decision
		Decision criteria (+) Yes (−) No (?) Lack of information (!) Check the criterion								Decision
			Compatible with all function	Meets specification requests	Realizability in principle	Permissible cost	Directly meets safety requirements	Preferred by the designer company	Sufficient information	Decision criteria (+) Resume the solution (−) Remove the solution (?) Gather information (!) Check the specification for changes
S1	1	+	+	+	?	+	−	−	Needs to be improved	−
S2	2	+	+	+	?	+	−	−	Needs to be improved	−
S3	3	+	+	+	?	+	+	−	Sufficient	+
S4	4	+	+	+	?	+	−	?	Needs to be improved	−
S5	5	+	+	+	?	+	−	?	Needs to be improved	−
S6	6	+	+	+	?	+	+	−	Sufficient	+
S7	7	+	+	+	?	+	−	−	Needs to be improved	−
S8	8	+	+	+	+	+	+	+	Sufficient	+

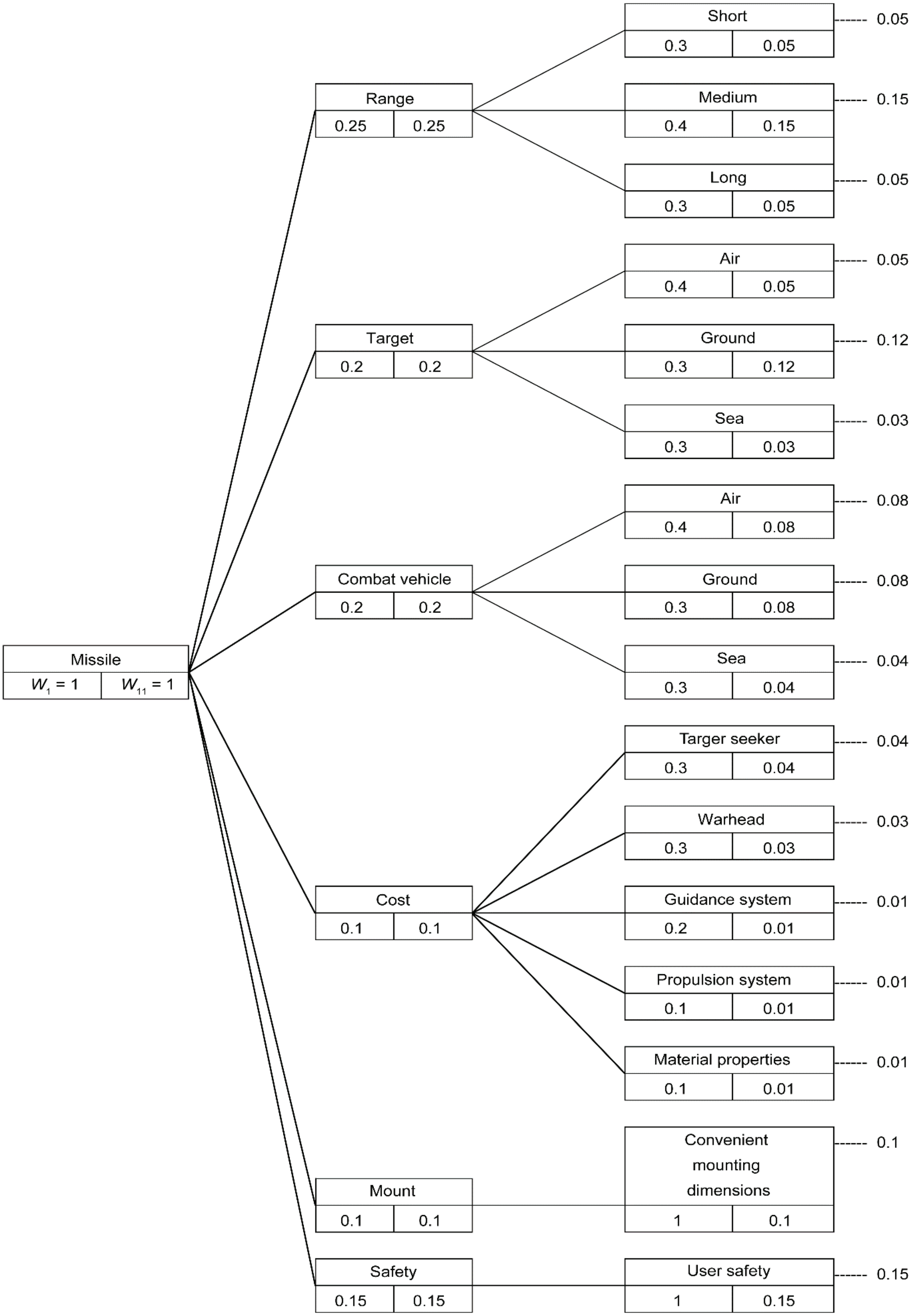


Figure 2. Objective tree created for missile design[2].

joining method. It has been observed that the possible solutions for the missile that will emerge from the study coincide with the characteristics of the missiles that have been applied today. Table 3 shows the eight solutions obtained from the missile design classification scheme in Table 2. This is obtained by first writing the numbers of the sub-function to which it is connected and then the numbers of the sub-systems connected to it.

3.6 Selecting Appropriate Combinations

A pre-selection is made using the selection card for the eight different solution variants obtained. The (+) sign was used for solutions that met the conditions, and the minus (−) sign was used for those that did not[16]. The three important solutions that meet the requirements in the selection card are coloured and shown on the selection card in Table 4.

3.7 Create and Show Solution Options

The solutions selected according to the operations on the selection card are S3, S6 and S8. The missile denoted by S3 is the SOM-B2, a long-range, air-to-surface Turkish national missile. It was built for heavily protected ground and sea targets. Its range is 100 nautical miles. The missile denoted by S6 is a HİSAR missile. It is a Turkish missile with a range of 25 km. It can be used in fixed-wing aircraft, rotary-wing aircraft and Unmanned Aerial Vehicle (UAV) systems. The missile denoted by S8 is the AGM-114 HELLFIRE, an air-to-surface missile. It has a heavily explosive anti-tank warhead. It ranges from 500 to 8000 m. It can be integrated into the helicopter. It has a solid-propellant rocket engine.

3.8 Evaluating Solution Options

The ‘cost-benefit analysis’ method was used to make a precise assessment between S3, S6 and S8. First, a tree of purposes was established. The tree of purposes was arranged in accordance with the design specification. A separate percentile was determined for each purpose with a total of 100%. These parameters may differ by design and designer. The total weight values appearing in the final components of the design tree should also yield a value of one. The total value of the components determined for missile design according to the needs is also one. Figure 2 shows the objective tree of purposes established for missile design.

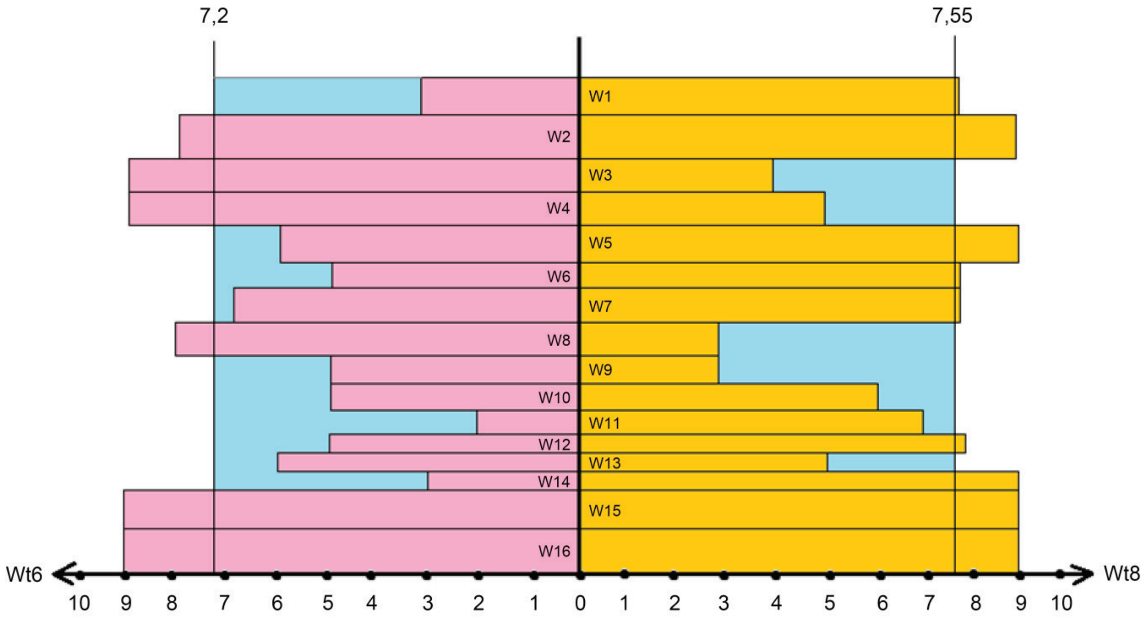


Figure 3. Value profile diagram[15].

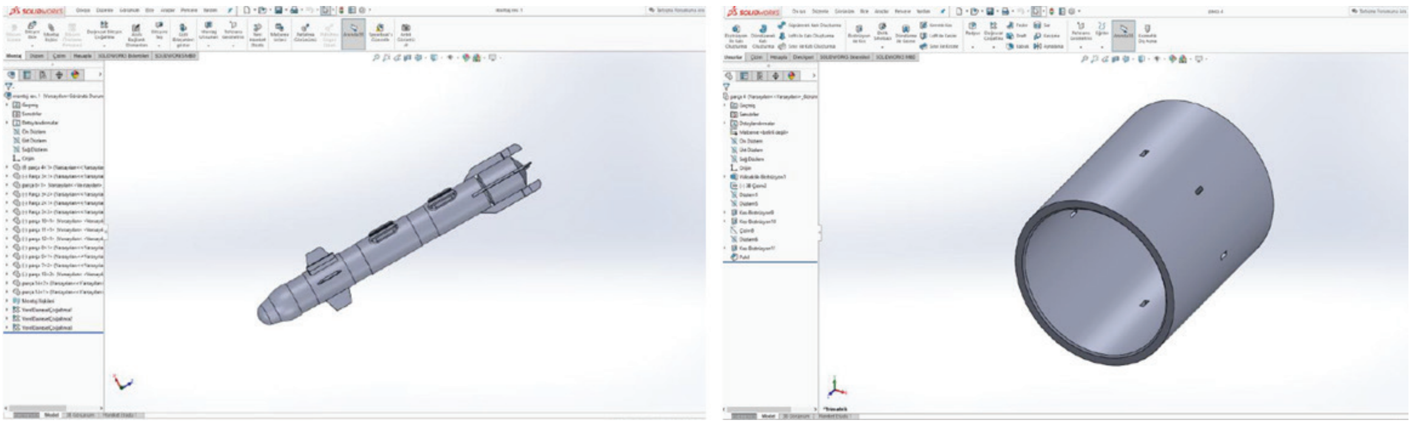
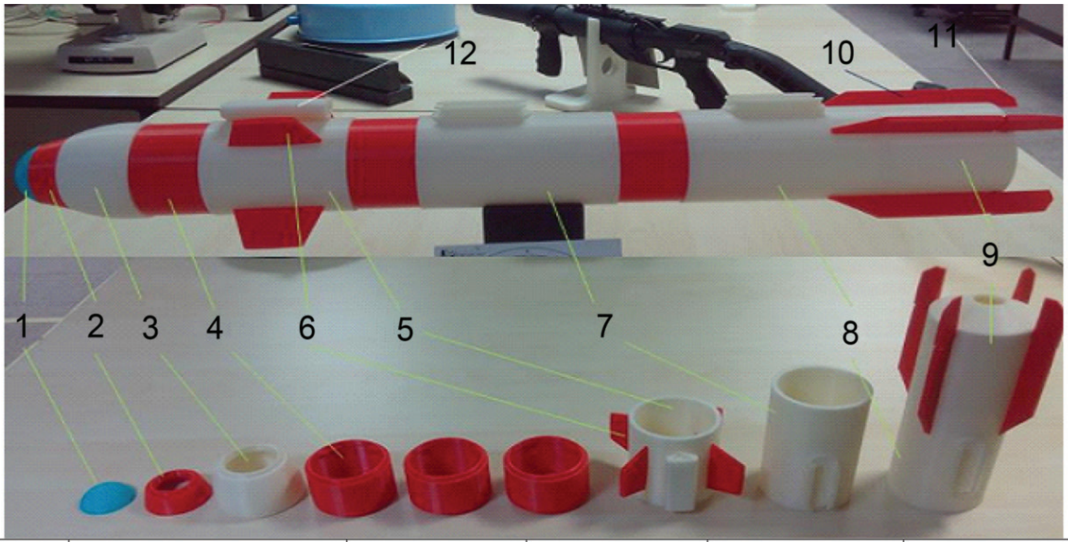
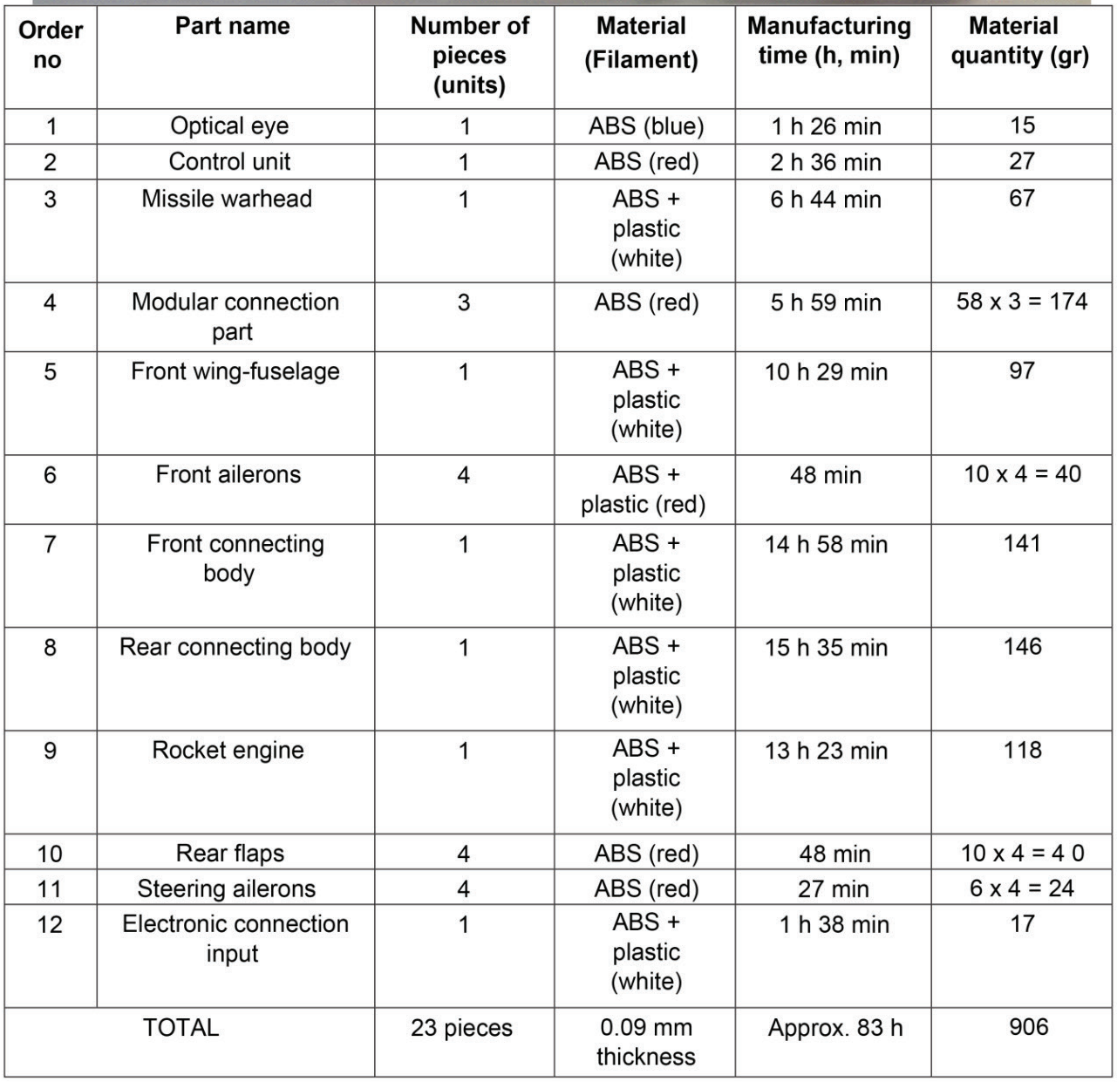


Figure 4. Assembly drawing and forewing fuselage solid model.





Order no	Part name	Number of pieces (units)	Material (Filament)	Manufacturing time (h, min)	Material quantity (gr)
1	Optical eye	1	ABS (blue)	1 h 26 min	15
2	Control unit	1	ABS (red)	2 h 36 min	27
3	Missile warhead	1	ABS + plastic (white)	6 h 44 min	67
4	Modular connection part	3	ABS (red)	5 h 59 min	58 x 3 = 174
5	Front wing-fuselage	1	ABS + plastic (white)	10 h 29 min	97
6	Front ailerons	4	ABS + plastic (red)	48 min	10 x 4 = 40
7	Front connecting body	1	ABS + plastic (white)	14 h 58 min	141
8	Rear connecting body	1	ABS + plastic (white)	15 h 35 min	146
9	Rocket engine	1	ABS + plastic (white)	13 h 23 min	118
10	Rear flaps	4	ABS (red)	48 min	10 x 4 = 4 0
11	Steering ailerons	4	ABS (red)	27 min	6 x 4 = 24
12	Electronic connection input	1	ABS + plastic (white)	1 h 38 min	17
TOTAL		23 pieces	0.09 mm thickness	Approx. 83 h	906

Figure 5. Assembly image of a missile training model and missile model printing basic data.

In the next step, a rubric is created using the criteria and values from the objective tree. All S3, S6 and S8 values were placed separately in the table, and a comparison was made. Scoring was made according to the problem definition and the desired characteristics for the missile training model. Table 5 shows the prepared evaluation. In the last row of the rubric table, W_t (value from the tree of objectives), Σ_{ad} (sum of the weighted values), Σ_d (sum of values) and ΣW_t (sum of values of the tree of objectives) values were calculated.

According to the results obtained, S6 and S8 have the highest scores in the evaluation table and their score is close to each other. Therefore, in the final stage, these two solutions will be compared. A value profile diagram was created for these two solutions. In the value profile diagram, the weak points of the solutions were compared, and the elimination process was performed. Figure 3 shows the value profile diagram.

According to the evaluation diagram, the optimum solution obtained from conceptual design is the 8th solution. In other words, the missile to be printed on the 3D printer will be an AGM-114 HELLFIRE-type missile. The general characteristics of the AGM-114 HELLFIRE air-to-surface anti-tank missile, which will be prototyped as an optimal solution, are as follows[17]:

- Manufacturer company: Lockheed Martin (USA)
- Type: Air-to-surface attack missile
- Guidance system: Semi-active/laser
- Warhead: 8 kg (high explosive anti-tank)
- Effective range: 500–8,000 m
- Length: 1.3 m
- Diameter: 178 mm
- Wing span: 33 cm
- Weight: 45 kg

4. SOLID MODELLING OF MISSILE COMPONENTS WITH SOLIDWORKS

The resulting missile model is designed in parts close to the actual missile dimensions, taking into account the dimensions of the 3D printer, where the production will be made. The model consists of 12 independent parts. However, this number increases to 23 using the fitting three times and the wing parts four times. The SolidWorks software was used for drawing, solid modelling and assembly of missile training model parts. Figure 4 shows the assembly drawing of the model created in SolidWorks and the solid model of the front wing body.

5. OUTPUT AND ASSEMBLY OF MISSILE COMPONENTS

The 3D printer's interface program was used to send the files containing the print pre-preparation settings to the printer via a secure digital memory card (SD Card). Figure 5 displays basic data, including the names, numbers, amount of filament used, and printing time of the missile model parts produced using 3D printing techniques as prototypes. The manufacturing process was executed considering the process parameters of the MEX (Material Extrusion) technology as defined in the ISO/ASTM 52900:2015(E) standard.

Figure 5 displays the missile model's final image after piecemeal production. The assembly process interlaces the parts with a tolerance of 0.1mm. The model has a diameter of Ø 85 mm and a length of 0.65 m, which is half the size of those used in the HELLFIRE missile.

6. CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

In this study, a missile model was created using a conceptual design method. The 'conceptual design' method based on the 'systematic design approach' proposed by Pahl and Beitz was used to design the air-to-surface missile model. The optimum solution based on the design specification was reached by following the basic steps of the conceptual design. The optimal solution is a missile model of the AGM-114 HELLFIRE-type. SolidWorks software was used in the 3D computer design of the missile model obtained by conceptual design. A design comprising 23 interlaced parts was created. Additive manufacturing technology was used to model the parts. The design created using SolidWorks software was saved as .stl files and transferred to a 3D printer. Two filaments were used in the printing: ABS and ABS-plastic mixture. Following the basic parts of the missile, the parts were printed using filaments of different colours. The parts were combined by plug-in connection to form the AGM-114 HELLFIRE missile model.

Weapon systems, 3D printing techniques and conceptual design are open to the development of new ideas. The results of this study show that new designs for weapon systems can be obtained and existing designs can be improved by using the conceptual design method. With further study, the number of design components considered in the conceptual design application can be increased. This can increase the number of meaningful solutions and enable the development of alternative designs. By integrating artificial intelligence technologies into the conceptual design process, more detailed, advanced and innovative solutions can be achieved. Models produced using additive manufacturing can also be used as training materials due to their modular structure, durability and light weight.

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Ms Nisa AY obtained graduate degree in Mechanical Engineering at Kırıkkale University. Her areas of interest include: Computer Aided Manufacturing (CAM), Computer Aided Design (CAD), additive manufacturing, systematic and conceptual design and composite materials.

In the current study, she conducted the literature review, data collection and analysis, design and production processes, evaluation of the results and article writing processes.

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In the current study, he conducted the data analysis, design and production processes and evaluation of the findings.