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Model-Based Concept Framework for Suborbital Human Spaceflight Missions

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Abstract

Projects of the New Space economy such as SpaceShipTwo and New Shepard are on their way to shifting the paradigms in space tourism and transportation. Being privately financed, they are also changing the way in which highly complex and formerly government-financed systems are now being developed. Looking to the future, we can envision humanity moving to space, an opportunity that will be available to many more of us as a result of these new paradigms. One of the core issues we encounter when we start the development of complex systems such as the suborbital transportation and space tourism systems is: what are the concepts available and how can these concepts be represented using strictly defined ontology and model semantics? In this work we present a model-based concept framework that aims to address this issue. First a concept framework methodology is presented, after which we demonstrate its applicability to suborbital human spaceflight missions – SpaceShipTwo and New Shepard. The analytical conceptual difference between these concepts is demonstrated. The proposed framework includes: the information that characterizes stakeholders and their needs; the solution-neutral environment (the problem statement) in which we formulate the functional intent; the solution-specific environment (solution statement) in which we see the possible solutions; the decomposition of such solution into internal elements and functions; and the concept of operations. Each one of these entries of the concept framework has a counterpart represented in conceptual modeling languages, such as Object-Process Methodology (OPM) or the System Modeling Language (SysML). Such a model-based concept framework encodes the core information required to define a suborbital tourism concept and represent it in a digital environment. We believe this will become a powerful tool to support the makers of architectural decisions that lead to concept and eventually to architecture.

Keywords: concept, conceptual design, model-based system engineering, suborbital systems, space tourism

1. Introduction

Model-based conceptual design (MBCD) is the "application of Model-Based Systems Engineering (MBSE) to the exploratory research and concept stages of the generic lifecycle" [1]. Our work is motivated by the desire to demonstrate how a model-based concept framework, developed based on system architecture principles [2], enables the representation of conceptual design information. This would create an opportunity to explore the alternative concepts for suborbital human spaceflight missions, keeping track of conceptual difference among competing options. The objective of this paper is to develop and present a unified concept framework, and demonstrate that when applied to alternative suborbital concepts it contains information about differences in alternative suborbital concepts, such as Virgin Galactic's SpaceShipTwo [3] and Blue Origin's New Shepard [4].

Since the creation of Ansari X Prize contest [5] a new market of suborbital tourism appeared on the map of space activities. Over the last two decades the dozens of projects were initiated, aiming at making suborbital spaceflight systems reliable and enjoyable for space travelers. Indeed, the suborbital spaceflight systems create not only the opportunity for a space tourism market, but also for such promising areas as point-to-point transportation. According to the estimates of Peeters [6] and the International Space University [7], suborbital transportation would reduce the time spent on New York - Tokyo route from the current 13 hours on a commercial airplane to 90 minutes on a suborbital vehicle. This would enable to attract those travelers who are more focusing on time savings, rather than ticket price.

The utility of the proposed concept framework is that if the system engineer adopts it, he or she will have a tool that digitally supports the design process. Another utility is that such a framework facilitates the analysis of complex systems, as well as synthesis of the systems under development.

On April 29, 2018 the Blue Origin company announced that its New Shepard's crew capsule reached an apogee of 107 km - the targeted altitude for the operations. On July 26, 2018 Virgin Galactic's VSS Unity (SpaceShipTwo) reached Mach 2.4 arriving at an apogee of 51 km. These accomplishments demonstrate a continuing competition in the suborbital space tourism sector, and the clear path to sustainable market.

Meanwhile, when we see a new suborbital space venture, or analyze an existing one, we observe a lack of common representation of conceptual information about the system. The information on each system is presented differently, depending on previous experience of system engineers of the specific project. This identifies a research opportunity: to create a more rigorous and digitally supported approach to the conceptual design phase. Thus, the specific objective of this paper is to demonstrate a model-based concept framework which supports conceptual design phase by encoding the conceptual information about multiple alternatives. This will be applied to suborbital space tourism concepts using a strictly defined ontology and model semantics.

This paper is organized as follows. In section 2 we discuss the system architecture methods that are used in the paper. Section 3 demonstrates unified framework that contains the entries of concept framework. In section 4 we apply the proposed framework to two suborbital projects, namely, Virgin Galactic's SpaceShipTwo and Blue Origin's New Shepard. We discuss the conclusions and the limitations of our work in section 5.

2. System architecture methods

In our paper we are applying the system architecture methods at the early stages of design process – conceptual design [2]. The central idea is to define "concept" as the mapping of form to function. "Conceptual design" is considered the movement from the solution-neutral to the solution-specific environment (see Figures 1 and 2) [8]. The system architecture approaches can be effectively encoded into the model-based environment, such as Object-Process Methodology (OPM) [9] or SysML [10]. We chose OPM, as it is representing the system graphically in a smaller number of diagrams compared to SysML. In our paper we apply the proposed concept framework to suborbital human spaceflight missions, representing them in a model-based environment.

In Figure 1 the three important entities of any system are identified. Any system can be described by means of an *operand*, *process*, and *form*. The *process* is the activity that changes the state of the *operand*. The *form* is an instrument that is used to perform the function (operand plus process). The details of these entries, among other entries of the concept framework are presented in Figure 2 and discussed in the next section.

In our paper we use the OPM notation. According to this modelling language, the operands and elements of form are objects represented by rectangles, while the processes are represented by ovals. The specialization link is denoted by white triangle, and the decomposition link is denoted by black triangle. Attributes are indicated by two triangles, a black one inside the white one. We will use the OPM notation throughout this paper.

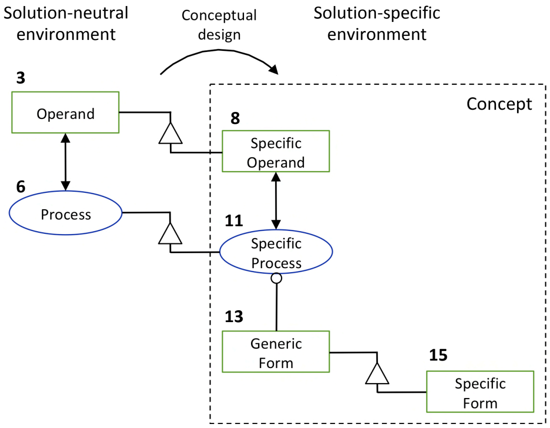
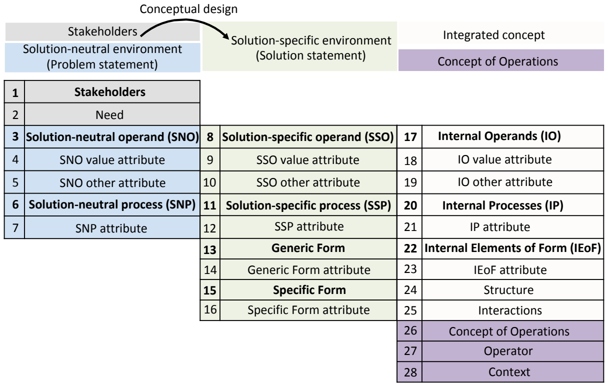


Fig. 1. Concept as a specific operand, process and form, specialized from solution-neutral information. Note that the numbers correspond to those in Figure 2. The notation is that of Object-Process Methodology (OPM)

3. Unified concept framework

The unified concept framework is presented in Figure 2, in which the entries of the framework are outlined. These 28 entries are spread among 5 assertions and marked by different colors in order to facilitate their identification with an assertion. For example, we can see that the first assertion (on stakeholder) contains two entries in the concept framework: the stakeholders and their need. By stakeholders we imply "any group or individual who can affect or is affected by the achievement of the organization's objectives" [11]. The second assertion (on solution-neutral environment) has five entries, numbered from 3 to 7, and is dedicated to the environment in which the solutions are not known [12, 13]. The main goal of this part of framework is to formulate the problem statement based on stakeholders' need.



Stakeholders Solution-neutral environment (Problem statement)		Solution-specific environment (Solution statement)		Integrated concept Concept of Operations	
1	**Stakeholders**				
2	Need				
3	**Solution-neutral operand (SNO)**	**8**	**Solution-specific operand (SSO)**	**17**	**Internal Operands (IO)**
4	SNO value attribute	9	SSO value attribute	18	IO value attribute
5	SNO other attribute	10	SSO other attribute	19	IO other attribute
6	**Solution-neutral process (SNP)**	**11**	**Solution-specific process (SSP)**	**20**	**Internal Processes (IP)**
7	SNP attribute	12	SSP attribute	21	IP attribute
		13	**Generic Form**	**22**	**Internal Elements of Form (IEoF)**
		14	Generic Form attribute	23	IEoF attribute
		15	**Specific Form**	24	Structure
		16	Specific Form attribute	25	Interactions
				26	Concept of Operations
				27	Operator
				28	Context

Fig. 2. Table view of the unified concept framework of 28 entries organized around five main assertions

The third assertion (on solution-specific environment) has nine entries, from 8 to 16, and is commonly known as the conceptual design [14, 15]. The main purpose of this part of the concept framework is to conceptualize the possible solution, or the alternative solutions by specializing the abstract information to a more concrete set of information.

The fourth assertion is dedicated to the integrated concept and is containing nine entries, from 17 to 25. By decomposing the solution's form into internal elements, the system architect can identify the internal functions fulfilled by such internal elements of form. Structure and interactions (entries 24 and 25) inform the relationships among the internal elements of forms in both physical and functional domain [16]. The fifth assertion deals with the concept of operations, having three entries from 26 to 28. This information encompasses the concept of operations (entry 26), the operator (entry 27), and the context (entry 28) under which the system is intended to operate [17].

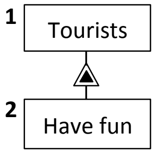
It is the hypothesis of our work that having the detailed information about each one of the entries of Figure 2 the system architect captures the core essence of the concept. This information can be effectively represented by means of the model-based approaches, and enables the development of systems at the conceptual stage in engineering environments, such as concurrent engineering design environment [18].

4. Model-based concepts for Virgin Galactic and Blue Origin systems

Applying our methodology to suborbital spaceflight systems, we start with the first entries of the concept framework: stakeholders and their needs (entries 1 and 2 of Figure 2). We define the stakeholders as the "tourists", who have a need "have fun" (see Figure 3). As we discussed earlier, the suborbital systems might also serve as a point-to-point transportation system [6], [7]. In this case the stakeholders would be the "travelers", who would have the need to "get somewhere". We will use the current tourism need as the reference.

Stakeholders		
1	**Stakeholders**	**Tourists**
2	Need	Have fun

a



b

Fig. 3. The first assertion of the Unified concept framework: table view (a) and OPM view (b)

Once we have decided on the first stakeholder entries of the concept framework, we may proceed with identification of solution-neutral environment's entries. In the solution-neutral we should stay as abstract as possible in order to allow for a broad space of alternatives and not to suggest any aspect of the solution. Thus, "entertaining" (entry 6) "individuals" (entry 3) is an appropriate solution-neutral's function that might lead to space tourism concepts. At this level of concept development the system architect is allowed to state the solution-neutral operand's value attribute (such as "enjoyment level") and other attributes (such as "number"); and solution-neutral process' attribute (such as "safely"). The full solution-neutral problem statement is to "increase the enjoyment level (i.e. entertain) of individuals, safely." (see Figure 4).

Solution-neutral environment (Problem statement)		
3	**Solution-neutral operand (SNO)**	**Individuals**
4	SNO value attribute	Enjoyment level
5	SNO other attribute	Number
6	**Solution-neutral process (SNP)**	**Entertaining**
7	SNP attribute	Safely

Fig. 4. The second assertion of the Unified concept framework in table view

Conceptual design is the movement from solution-neutral to solution-specific environment. In other words, conceptual design is the reasoning about how to specialize the operand and process of the second assertion (see Figure 2) to the more specific ones in the third assertion. The specialized operand/process are more concrete. As such, the specialized operand of solution-neutral operand "individuals" would be "passengers"; while the specialized process of solution-neutral process "entertaining" would be "flying". Note that the attributes are inherited: if the solution-neutral operand/process has had some attribute, it is inherited by the solution-specific operand/process. So flying must be "safe." Another major difference between the solution-neutral and solution-specific environments is the presence of form, the instrument that executes the specific function "flying passengers". The generic form (entry 13) is "Suborbital vehicle", and the specific form (entry 15) is either "Virgin Galactic system" or "Blue Origin system". In other words, at the 15th entry of the concept framework we start distinguishing the alternative solutions for the same solution-neutral and solution-specific functions that aim to fulfill the needs of stakeholders. This information is summarized in Figure 5 (table view) and Figure 6 (OPM view).

Solution-specific environment
(Solution statement)

8	**Solution-specific operand (SSO)**	**Passengers**
9	SSO value attribute	Enjoyment level
10	SSO other attribute	Number
11	**Solution-specific process (SSP)**	**Flying**
12	SSP attribute	Safely
13	**Generic Form**	**Suborbital vehicle**
14	Generic Form attribute	Cost
15	**Specific Form**	**Virgin Galactic/Blue Origin**
16	Specific Form attribute	Cost

Fig. 5. The third assertion of the Unified concept framework in a table view

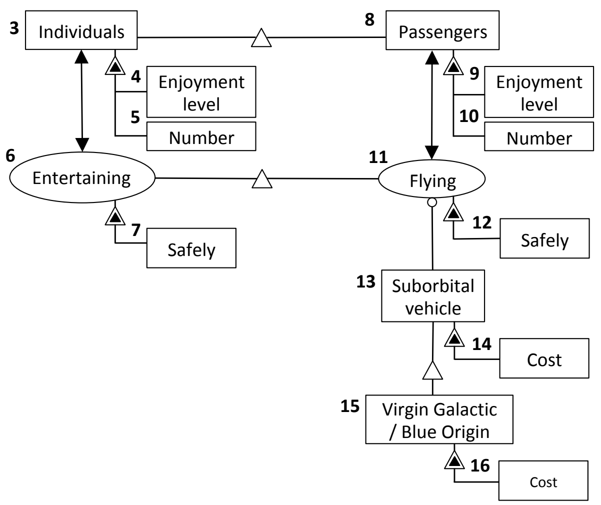


Fig. 6. The third assertion of the Unified concept framework in an OPM view

In our work we are focusing on the model-based representation of the integrated concept using the unified framework (Figure 2). This allows us to visualize two concepts on consistent levels of granularity [19], and retrospectively to analytically measure the conceptual difference between the concepts [20].

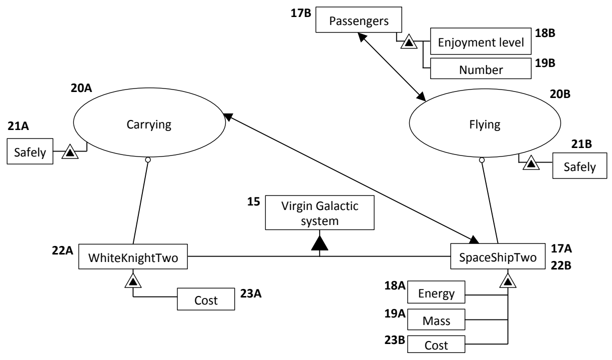
The integrated concepts for Virgin Galactic system and Blue Origin system projects at the first level decomposition are shown in Figures 7 to 10. At this level of decomposition the system engineer can identify the internal elements of form (entry 22) that serve as the instruments for corresponding internal processes (entry 20) acting on internal operands (entry 17).

The Figure 7 demonstrates the decomposition of the specific form “Virgin Galactic system” (entry 15) into the internal elements of form (entry 22) “WhiteKnightTwo” and “SpaceShipTwo”, each one of which perform its own function. For example, WhiteKnightTwo’s internal process is “carrying” (entry 20A), and internal operand is “SpaceShipTwo” (entry 17A) - see Figure 7(a). SpaceShipTwo’s internal process is “flying” (entry 20B), and internal operand is “passengers” (entry 17B) – see right hand side of Figure 7(a). The attributes of the internal elements/processes/operands are shown in both representations of the first level decomposition – table in Figure 7(a) and OPM in Figure 7(b). Note that sometimes the same object might be both operand and instrument, as it is in case of SpaceShipTwo. In one case the SpaceShipTwo is an operand, as it is in column A of Figure 7(a), in another case – an instrument, as it is in column B of Figure 7(a). This information is also encoded in Figure 7(b), in which the block “SpaceShipTwo” has both indications - 17A, 22B.

Integrated concept
First level decomposition

	A: WhiteKnightTwo	B: SpaceShipTwo
17	**SpaceShipTwo**	**Passengers**
18	Energy	Enjoyment level
19	Mass	Number
20	**Carrying**	**Flying**
21	Safely	Safely
22	**WhiteKnightTwo**	**SpaceShipTwo**
23	Cost	Cost
24	See diagram (Figure 8)	See diagram (Figure 8)
25	See diagram (Figure 8)	See diagram (Figure 8)

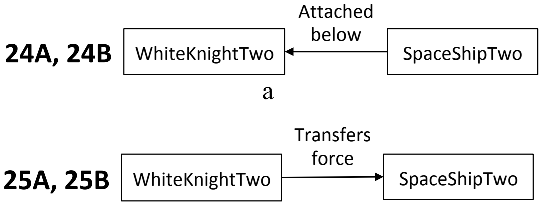
a



b

Fig. 7. The integrated concept (fourth assertion) at the first level decomposition for Virgin Galactic system in a table view (a) and in an OPM view (b). The entries' names are described in Figure 2

The information about structure (entry 24) and interactions (entry 25) at the first level decomposition is summarized in Figure 8. The *structure* is the physical/logical relationship of elements to each other. The *interactions* have a dynamic nature as something is shared or exchanged during operations.



a

b

Fig. 8. The structure (a) and interactions (b) (fourth assertion) at the first level decomposition for Virgin Galactic system

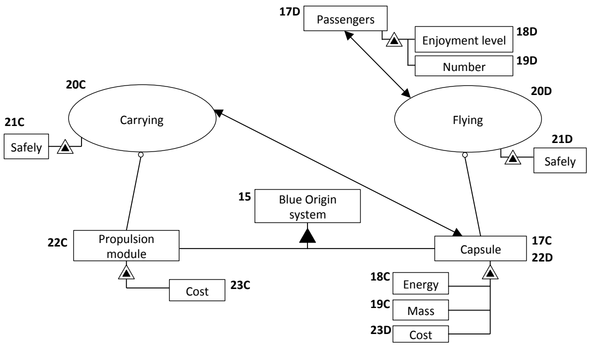
From Figure 8 we can see that SpaceShipTwo is "attached below" of WhiteKnightTwo. The WhiteKnightTwo "transfers force" to SpaceShipTwo.

In Figure 9 we capture the first level decomposition of the specific form "Blue Origin system" (entry 15) into the internal elements of form (entry 22) "Propulsion module" and "Capsule". From both of these Figures we see that the internal elements of form "propulsion module" (entry 22C) and "capsule" (entry 22D) perform the internal functions "carrying capsule" (entries 20C plus 17C) and "flying passengers" (entries 20D plus 17D), correspondingly.

Integrated concept
First level decomposition

	C: Propulsion module	D: Capsule
17	**Capsule**	**Passengers**
18	Energy	Enjoyment level
19	Mass	Number
20	**Carrying**	**Flying**
21	Safely	Safely
22	**Propulsion module**	**Capsule**
23	Cost	Cost
24	See diagram (Figure 10)	See diagram (Figure 10)
25	See diagram (Figure 10)	See diagram (Figure 10)

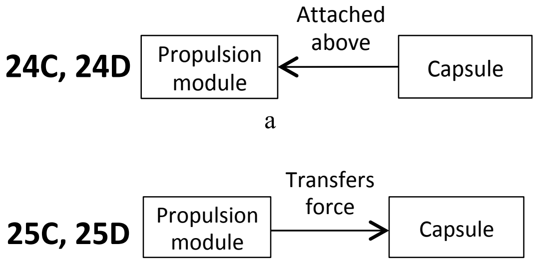
a



b

Fig. 9. The integrated concept (fourth assertion) at the first level decomposition for Blue Origin system in a table view (a) and in an OPM view (b). The entries' names are described in Figure 2

The information about structure (entry 24) and interactions (entry 25) at the first level decomposition is summarized in Figure 10. From this Figure we can see that Capsule is "attached above" the Propulsion module. The Propulsion module "transfers force" to Capsule.



a

b

Fig. 10. The structure (a) and interactions (b) (fourth assertion) at the first level decomposition for Blue Origin system

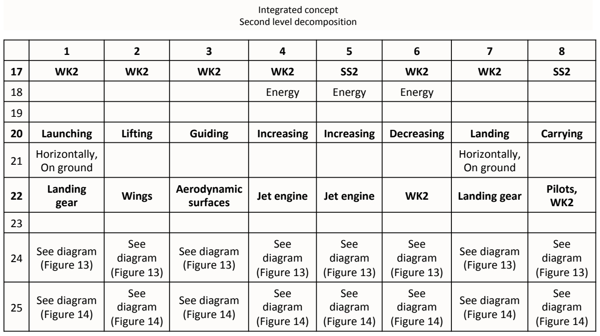
From Figures 7(b) and 9(b) we may see that conceptually the Virgin Galactic and Blue Origin concepts are identical at the first level of decomposition for the entries 17 to 23 of the concept framework, so as the system designers we have to go to the next level of decomposition to start distingushing the difference between these concepts. Concerning the entries 24 (structure) and 25 (interactions) the concepts are different: for instance, SpaceShipTwo "attached below" WhiteKnightTwo (see Figure 8), while Capsule "attached above" Propulsion module (see Figure 10).

One of the benefits of the system architecture principles is that they remain the same at all levels of decomposition [21]. From a careful examination of the Figures 7(a) and 9(a) we may notice that the internal elements of form (entries 22A, 22B), namely, "WhiteKnightTwo" and "SpaceShipTwo" for Virgin Galactic system, and "Propulsion module" and "Capsule" (entries 22C, 22D) for Blue Origin system can be further decomposed into their own internal elements, processes, and operands.

Consider the decomposition of the Virgin Galactic's internal elements of form "WhiteKnightTwo" and "SpaceShipTwo" (see Figure 11) into the second level decomposition. If we consider the example of WhiteKnightTwo in details - see Figure 11(a), we will see that this internal element of form is further decomposed into five internal elements: landing gear (entry 22A1), wings (entry 22A2), aerodynamic surfaces (entry 22A3), jet engine (entry 22A4), and pilots (entry 22A5). Each one of these forms perform its own internal function, or internal functions: "launching WhiteKnightTwo", "lifting WhiteKnightTwo", "guiding WhiteKnightTwo", "increasing (the energy of) WhiteKnightTwo", "increasing (the energy of) SpaceShipTwo", "landing WhiteKnightTwo", "carrying

SpaceShipTwo", correspondingly. Note two important observations: landing gear performs two internal functions; and the instrument of decreasing the WhiteKnightTwo's energy is its airframe (WK2 itself).

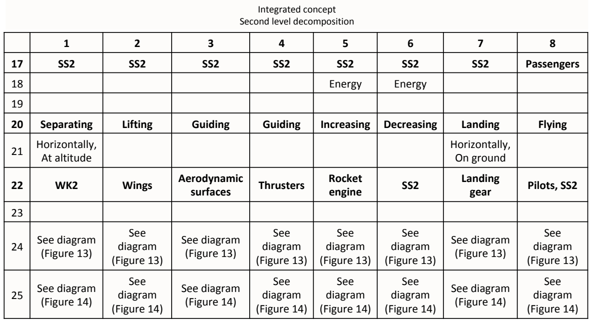
If we consider the example of SpaceShipTwo in details - see Figure 11(b), we will notice that this internal element of form is further decomposed into six internal elements: wings (entry 22B1), aerodynamic surfaces (entry 22B2), thrusters (entry 22B3), rocket engine (entry 22B4), landing gear (entry 22B5), and pilots (entry 22B6). The performing functions are: "lifting SpaceShipTwo", "guiding SpaceShipTwo", "guiding SpaceShipTwo", "increasing (the energy of) SpaceShipTwo", "decreasing (the energy of) SpaceShipTwo", "landing SpaceShipTwo", and "flying passengers", respectively. Note that the instrument of "separating SpaceShipTwo" is WhiteKnightTwo.



Integrated concept
Second level decomposition

	1	2	3	4	5	6	7	8
17	**WK2**	**WK2**	**WK2**	**WK2**	**SS2**	**WK2**	**WK2**	**SS2**
18				Energy	Energy	Energy		
19								
20	**Launching**	**Lifting**	**Guiding**	**Increasing**	**Increasing**	**Decreasing**	**Landing**	**Carrying**
21	Horizontally, On ground						Horizontally, On ground	
22	**Landing gear**	**Wings**	**Aerodynamic surfaces**	**Jet engine**	**Jet engine**	**WK2**	**Landing gear**	**Pilots, WK2**
23								
24	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)
25	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)

a



Integrated concept
Second level decomposition

	1	2	3	4	5	6	7	8
17	**SS2**	**SS2**	**SS2**	**SS2**	**SS2**	**SS2**	**SS2**	**Passengers**
18					Energy	Energy		
19								
20	**Separating**	**Lifting**	**Guiding**	**Guiding**	**Increasing**	**Decreasing**	**Landing**	**Flying**
21	Horizontally, At altitude						Horizontally, On ground	
22	**WK2**	**Wings**	**Aerodynamic surfaces**	**Thrusters**	**Rocket engine**	**SS2**	**Landing gear**	**Pilots, SS2**
23								
24	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)	See diagram (Figure 13)
25	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)	See diagram (Figure 14)

b

Fig. 11. The integrated concept (fourth assertion) at the second level decomposition for Virgin Galactic's "WhiteKnightTwo" (a) and "SpaceShipTwo" (b). The entries' names are described in Figure 2

The OPM representation of the same information as it is indicated in Figures 11(a) and 11(b) is presented in Figure 12. We may see that the information encoded into the OPM view is much more compact and readable, comparing to the table format. Note that we do not include the information about all inherited attributes of the internal operands, internal processes, and internal elements of form, yet there is the information about type of launch and landing with corresponding attributes. Thus, WhiteKnightTwo together with SpaceShipTwo launches horizontally from ground and lands horizontally on ground; while SpaceShipTwo launches horizontally at altitude, and lands horizontally on ground.

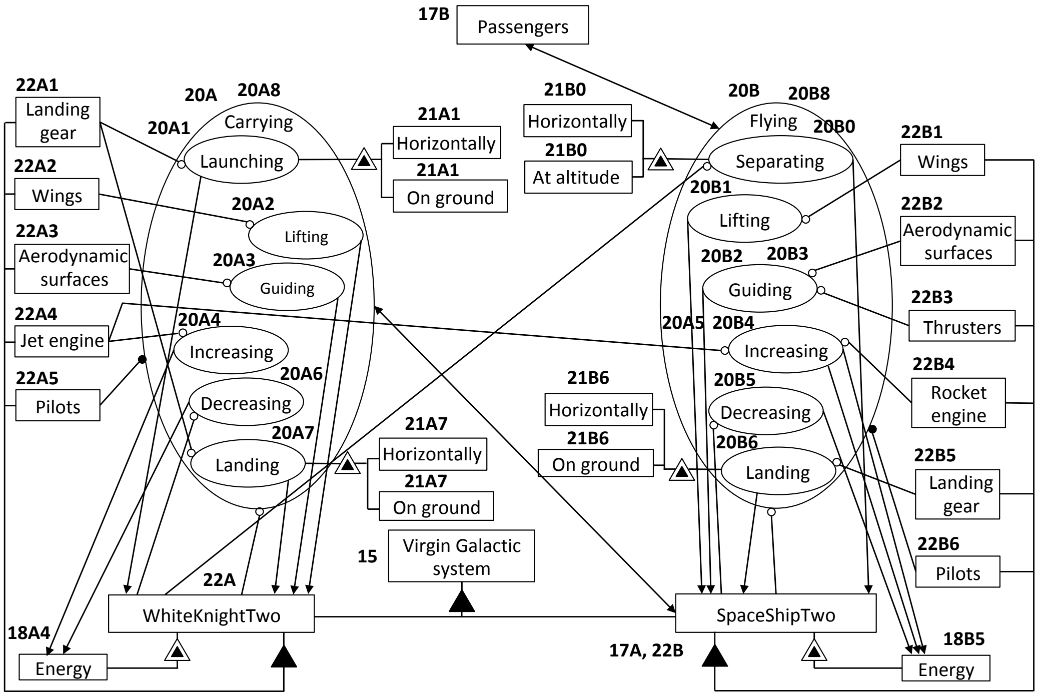


Fig. 12. OPM representation of the integrated concept (fourth assertion) at the second level decomposition for Virgin Galactic's "SpaceShipTwo" and "WhiteKnightTwo"

The structure and interactions among the second level elements of form (entries 24 and 25, respectively) are presented in Figures 13 and 14, respectively. This information represents the second level decomposition.

For instance, from the Figure 13 we can see that the physical connection between jet engine and wings is that the jet engine is "attached below" of wings. The aerodynamic surfaces "attached at rear" of WhiteKnightTwo. The pilots are "within" the WhiteKnightTwo, and so on.

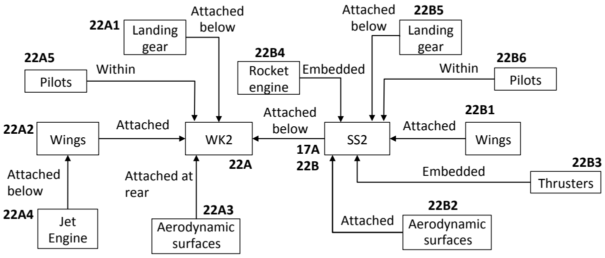


Fig. 13. OPM representation of the integrated concept (fourth assertion) at the second level decomposition's structure information for the Virgin Galactic's "SpaceShipTwo" and "WhiteKnightTwo"

From the Figure 14 we may notice that, for example, pilots "provide input" to WhiteKnightTwo; while wings "provide lift" to SpaceShipTwo.

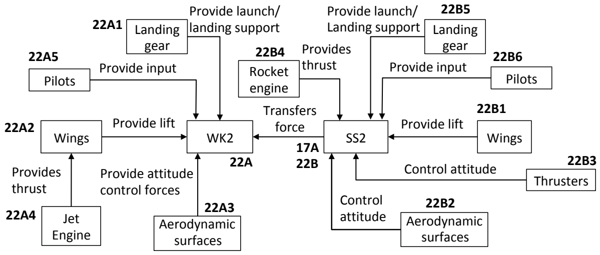
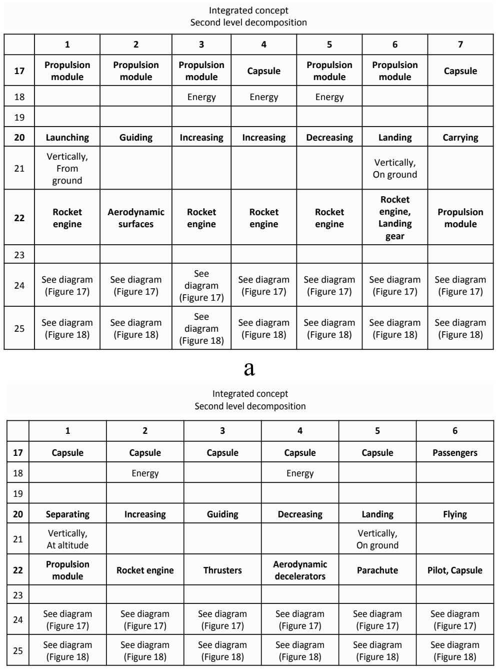


Fig. 14. OPM representation of the integrated concept (fourth assertion) at the second level decomposition's interactions information for the Virgin Galactic's "SpaceShipTwo" and "WhiteKnightTwo"

Consider the decomposition of the Blue Origin's internal elements of form "Propulsion module" and "Capsule" (see Figure 15) into the second level decomposition. If we consider the example of Propulsion module in details - see Figure 15(a), we will see that this internal element of form is further decomposed into three internal elements: rocket engine (entry 22C1), aerodynamic surfaces (entry 22C2), and landing gear (entry 22C3). The rocket engine performs the number of internal functions: "launching Propulsion module", "increasing (the energy of) Propulsion module", "increasing (the energy of) Capsule", "decreasing (the energy of) Propulsion module", and "landing Propulsion module"; the internal function of the aerodynamic surfaces is "guiding propulsion module"; the internal function of landing gear is "landing Propulsion module". Note that the instrument of "carrying Capsule" is Propulsion module itself.

The internal elements of form "Capsule" - see Figure 15(b) - is further decomposed into four internal elements: thrusters (entry 22D1), aerodynamic decelerators (entry 22D2), parachute (entry 22D3), and pilot (entry 22D4). Their internal functions are "guiding capsule", "decreasing (the energy of) capsule", "landing capsule" and "flying passengers", respectively. Note that the instrument of separating capsule is propulsion module, and that the instrument of increasing the energy of capsule is rocket engine of propulsion module.



Integrated concept
Second level decomposition

	1	2	3	4	5	6	7
17	**Propulsion module**	**Propulsion module**	**Propulsion module**	**Capsule**	**Propulsion module**	**Propulsion module**	**Capsule**
18			Energy	Energy	Energy		
19							
20	**Launching**	**Guiding**	**Increasing**	**Increasing**	**Decreasing**	**Landing**	**Carrying**
21	Vertically, From ground					Vertically, On ground	
22	**Rocket engine**	**Aerodynamic surfaces**	**Rocket engine**	**Rocket engine**	**Rocket engine**	**Rocket engine, Landing gear**	**Propulsion module**
23							
24	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)
25	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)

a

Integrated concept
Second level decomposition

	1	2	3	4	5	6
17	**Capsule**	**Capsule**	**Capsule**	**Capsule**	**Capsule**	**Passengers**
18		Energy		Energy		
19						
20	**Separating**	**Increasing**	**Guiding**	**Decreasing**	**Landing**	**Flying**
21	Vertically, At altitude				Vertically, On ground	
22	**Propulsion module**	**Rocket engine**	**Thrusters**	**Aerodynamic decelerators**	**Parachute**	**Pilot, Capsule**
23						
24	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)	See diagram (Figure 17)
25	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)	See diagram (Figure 18)

b

Fig. 15. The integrated concept (fourth assertion) at the second level decomposition for Blue Origin's "Propulsion module" (a) and "Capsule" (b). The entries' names are described in Figure 2

In Figure 16 we demonstrate the OPM representation of the same information as it is indicated in Figures 15(a) and 15(b). Similarly to the Virgin Galactic case, we do not include the information about the inherited internal operand's, internal processes', and internal elements of form's attributes, yet there is the information about type of launch and landing with corresponding attributes. Thus, Propulsion module together with Capsule launches vertically from the ground and lands vertically on the ground; while Capsule separates at altitude and lands vertically on the ground. Such representation captures the difference between Virgin Galactic's and Blue Origin's projects using the conceptual modeling language.

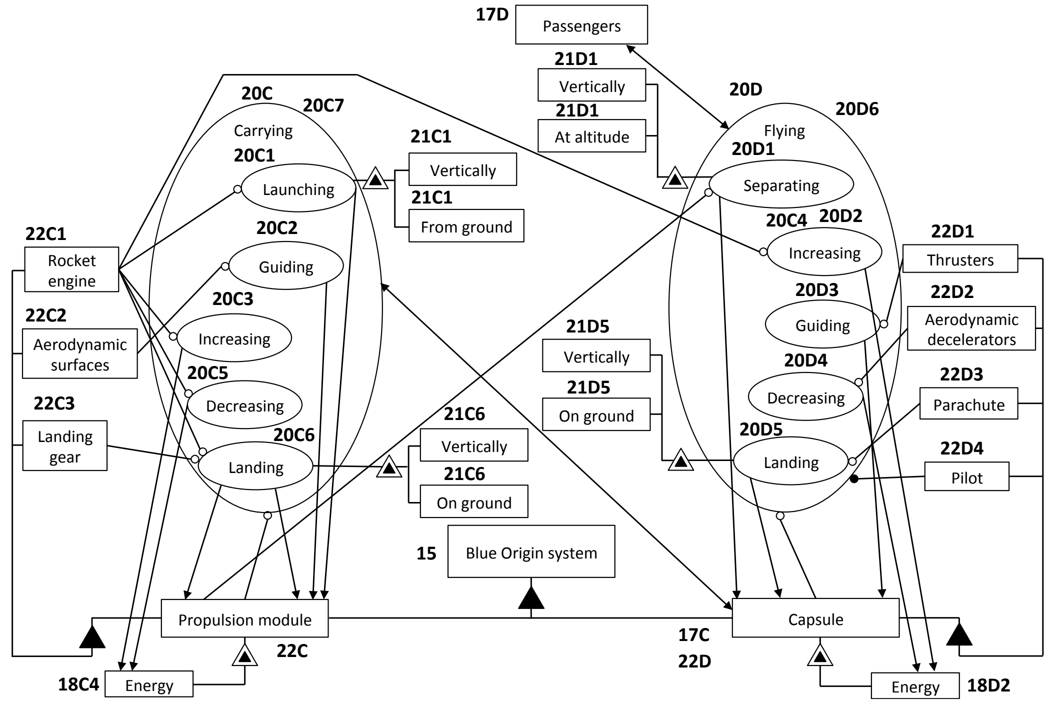


Fig. 16. OPM representation of the integrated concept (fourth assertion) at the second level decomposition for Blue Origin's "Propulsion module" and "Capsule"

The structure and interactions for the second level elements of form (entries 24 and 25, respectively) are presented in Figures 17 and 18, respectively. This information represents the second level decomposition.

For example, Figure 17 informs us that for New Shepard thrusters "embedded" into capsule; while capsule is "attached" to propulsion module; and rocket engine is "embedded" into the propulsion module.

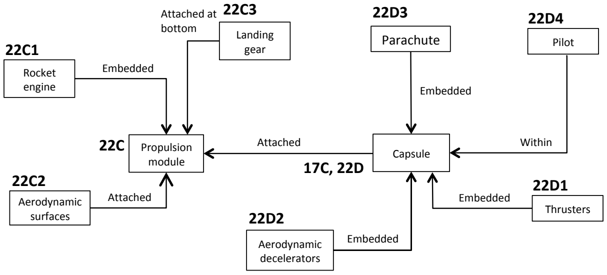


Fig. 17. OPM representation of the integrated concept (fourth assertion) at the second level decomposition's structure information for the Blue Origin's "Propulsion module" and "Capsule"

In regards to the interactions, the Figure 18 illustrates that capsule "transfers force" to the propulsion module; while rocket engine "provides thrust" to propulsion module of New Shepard.

Both the structure and the interactions data are important, as they convey the information about the physical and functional relationships among the elements.

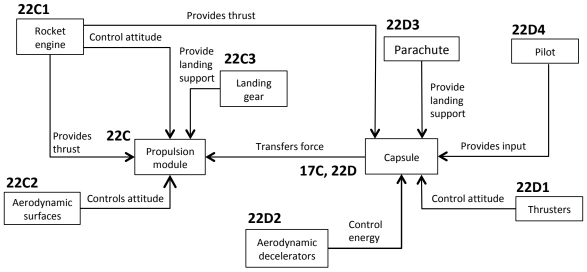


Fig. 18. OPM representation of the integrated concept (fourth assertion) at the second level decomposition's interactions information for the Blue Origin's "Propulsion module" and "Capsule"

Comparing the Figures 12 and 16 we may notice the conceptual difference between both concepts. It is important to note that this difference appears at the second level of the decomposition. From this figures we may see not only the different internal elements that perform the same internal functions at the second level decomposition but also such information about conceptual difference as the way by which the specific concept performs the internal function "decreasing (the energy of) the module", for example. As such in case of Virgin Galactic concept the airframe of WhiteKnightTwo decreases its energy, while in case of Blue Origin concept the Propulsion module's rocket engine both increase and decrease the energy of propulsion module.

The utility of the model-based representation is that it allows us to clearly see what exactly form performs what function, and what internal form performs what internal function.

This concludes the enumeration of the information that would be contained in the model-based representation of an integrated concept.

The fifth and last assertion of the concept framework is the concept of operations (see Figure 2). This assertion includes the ConOps itself (entry 26), the operator (entry 27), and the context (entry 28); and is summarized in Figure 19, which is a table view of ConOps assertion.

Concept of Operations	
26	See diagrams (Figures 20, 21)
27	Pilots
28	See diagrams (Figures 22, 23)

Fig. 19. ConOps assertion (fifth assertion) for both alternatives in a table view

The ConOps with the emphasis on SpaceShipTwo is shown in Figure 20. From this figure we can see that the Virgin Galactic system launches from the Mojave spaceport, reaches an altitude of 15km, at which the SpaceShipTwo separates from the WhiteKnightTwo. Then SpaceShipTwo climbs for about 90 seconds at the velocity of 4000 km/h to achieve the altitude of 100 km. Once there, it lofts to 110 km, after which it decelerates, unfolding the unique re-entry system. At the final stages of the mission the SpaceShipTwo performs the unpowered glide and finally lands back at the Mojave spaceport.

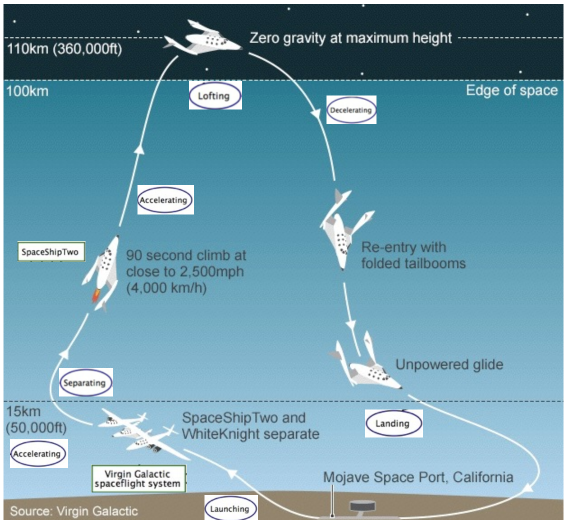


Fig. 20. Concept of Operations (fifth assertion) for Virgin Galactic system

The model-based representation reveals the key processes occurring during the operations of the system: "launching", "accelerating", "separating", "accelerating", "lofting", "decelerating", and "landing" indicated by process oval annotation in Figure 20.

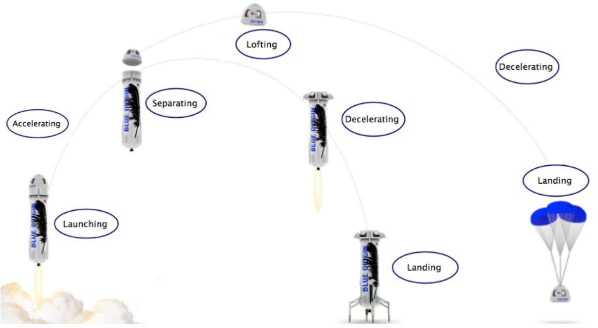


Fig. 21. Concept of Operations (fifth assertion) for Blue Origin system

The ConOps for the Blue Origin system is pictured in Figure 21. The both New Shepard's propulsion module and capsule are launched from the pad, after which the capsule separates from the propulsion module. Then the propulsion module decelerates and lands by means of rocket engine, while the capsule lands using the parachute system. The key processes illustrated by process ovals in Figure 21 are "launching", "accelerating", "separating", "lofting", "decelerating", and "landing".

The operator (entry 27) is the person who is using the system [2]. In both cases, for the Virgin Galactic system and for the Blue Origin system, the operators are the pilots.

The *context* surrounds the form of the system. In context we include all those systems that are relevant to system and its operations, sometimes called accompanying [2] or enabling systems [22]. In Figures 22 and 23 the context for both alternative concepts are shown. We see that the system boundary distinguishes the system of interest from other systems that are relevant and should be taken into account.

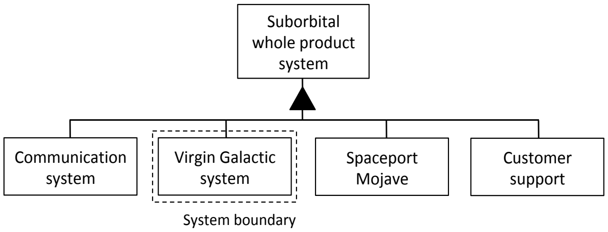


Fig. 22. Context (fifth assertion) for Virgin Galactic system

Consider the example of Virgin Galactic system presented in Figure 22. From this figure we notice that the "Virgin Galactic system" is inside the system boundary, which is clear as this is the system under exploration. There are number of systems that are outside of system boundary, but relevant to it and should also be considered – such as the "Communication system", "Spaceport Mojave", and "Customer support". Thus the context is important, as none of the systems operate alone, especially in our age of connectivity when systems are interacting with each other, support each other, and inform each other.

Figure 23 demonstrates the context for the Blue Origin system. We may notice that this system is launched from the Corn Ranch Spaceport.

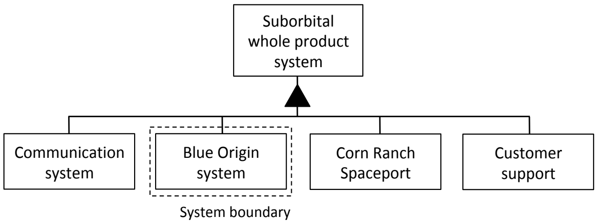


Fig. 23. Context (fifth assertion) for Blue Origin system

5. Conclusions

In this paper we proposed a model-based concept framework and demonstrated that it can be effectively used to capture the conceptual information about alternative concepts. We also demonstrated how this framework can be applied to the Virgin Galactic and Blue Origin systems. We have shown how, based on the stakeholders' needs, the system architect can progressively move the design process to the formulation of the abstract solution-neutral function that is further specialized to the solution-specific information containing the possible alternative solutions for stated problem. The information for various concepts can be represented in the grid of Figures 2, 3A, 4, 5, 7A, 9A, 11, 15, 19, or graphically (as in Figures 3B, 6, 7B, 8, 9B, 10, 12, 13, 14, 16, 17, 18, 22, 23) and on the same level of granularity for systems such as Virgin Galactic and Blue Origin. As such, we can see the distinctive features between SpaceShipTwo and New Shepard.

It is a finding of this work that there is actually a relatively large body of information necessary to document a concept. This in contrast with conventional practice, which usually captures a concept in a "tag line" (like Blended Wing Body) or a sketch. The inference is that in such conventional representations there must be a great deal of tacit knowledge, which when make explicit requires much more information to represent.

This work might have several aspects of utility. One is the ability to encode textual information into a model-based environment that keep the same semantics and level of granularity for the multiple alternative concepts. This makes it possible to engage the concurrent engineering design environment in earlier, conceptual stages of the design process.

We believe that the proposed approach will serve the purpose of facilitating the development of new systems, as well as the exploration of the existing ones.

Our approach has some limitations. The first lies in the necessity to include the specialists from a wide range of engineering fields into the design group aimed at the development of a specific concept. This requires them to operate using the same ontology and semantics, and using the same principles for encoding the graphical and textual information. Although in our paper we proposed the strictly defined approach to this problem, the issue with a team formation is still to be explored. Thus, this is a potentially promising direction of the future research.

Another limitation deals with the ability of human designer to narrow down the set of alternative solutions taking into account the whole spectrum of possibilities and eliminating the potential bias based on experience and personal preferences.

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