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A ROADMAP WITH INTEGRATED METHODS AND TOOLS TO ENABLE SET-BASED DESIGN

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Abstract— Over the past decade, researchers have shown an increased interest in Set-Based Design motivated by the potential benefits of shortening product development time while creating robust products. Despite the growing number of publications around the topic, most of them have focused on practical applications, leaving an area of opportunity to explore theoretical development. Many authors have suggested the use of different methods and tools to enable Set-Based Design. However, the techniques are usually applied individually, missing the chance to combine them in a systematic way. Therefore, the necessity of proposing roadmaps depicting how to integrate methods and tools to enable Set-Based Design is here identified. This paper integrates the GFIS (Given-Find-In Order To-Subjected To) Method for Problem Statement, Nondimensionalization with Causal Mapping, Dimensionless Trade-off Curves and Labeled Fuzzy Sets. These methods and tools are meant to help the designer listing key parameters and variables, identifying main interactions, mapping the design space, and finding a feasible and preferred design. A band brake design problem is presented to depict the application of the proposed roadmap with the intention of guiding the designer in the decision-making process, going from understanding the problem's requirements and limitations to achieving robust solutions. This work describes a series of steps that contribute to facilitate handling uncertainty, feasibility, and preference. The roadmap developed is applied to a band brake design problem as an example.

Set-Based Design; Set-Based Concurrent Engineering; Lean Design; Problem Statement Methods; Causal Mapping; Trade-off Curves; Labeled Fuzzy Sets

I. INTRODUCTION

Set-Based Design (SBD) is a design approach that has drawn the interest of researchers over the past 20 years and has seen a noticeable growth in publications during the last decade [1]. SBD can be decomposed in five aspects: solution space exploration and set-narrowing, design space mapping, designing for a set of environments, set-based communications and set-based concurrent engineering (SBCE) [2].

By covering these five aspects, the design process becomes more effective and more robust, allows finding more optimal solutions and eliminating rework [3,4]. Due to the mentioned benefits that SBD presents, it has been related to Lean Product and Development (LPD) [5] and it has been identified as one of the five LPD core enablers [6]. The key aspect of the relationship between SBD and LPD is that SBD allows more flexibility to make decisions in the early stages of a project [4], where their impact is the largest [3]. Since some companies spend around 70 to 80% of their development effort on loopbacks correcting wrong decisions made in early stages [7], it is clear why SBD has been seen as an alternative to cut costs, reduce rework, and increase profit [5].

There are other methods that are also intended to shorten developing times and bring down costs. The Critical Path Method (CPM) and the Linear Scheduling Model (LSM) are examples of methods that look to reduce risk, improve efficiency and have more economical gain [8]. While these methods share some similarities with SBD such as working in parallel and aiming to delay non-critical decisions, CPM and LSM focus more on finding the optimal order of activities and resources allocation that leads to an earlier completion of the project, which should end in less expenses. On the other hand, SBD focuses on design flexibility and enhanced communication between members of a project to facilitate making decisions, which should lead to less time and resources spent to achieve an optimal design.

The number of publications related to SBD or SBCE has been increasing, especially in the past 10 years. Most of them have focused on methods that facilitate SBCE, which opens the opportunity to explore theoretical development [1]. Therefore, this paper proposes the integration of four methods and tools to generate a roadmap for Set-Based Design. These are the GFIS Method for Problem Statement [9], Nondimensionalization with Causal Mapping [10], Dimensionless Trade-off Curves [11] and Labeled Fuzzy Sets [12].

The combination of the methods and tools mentioned above are intended to assist the designer in the early stages of product development, helping to identify critical parameters, variables, equations, and interactions. Then, this information is used to map the design space, allowing to generate multiple alternatives, and selecting the most optimal according to an established preference.

The paper is organized as follows. Section II describes in detail the four methods and tools, and how they are integrated. In Section III, a band brake design problem is presented to illustrate the application of the proposed roadmap. Section IV discusses the results obtained from the design problem and potential adaptations to other kind of problems. Finally, in Section V, conclusions and areas of future research are mentioned.

II. A SET-BASED DESIGN ROADMAP

While SBD contributes to reduce rework and facilitates finding preferred solutions among feasible ones, it has two main limitations. The first one is that applying isolated principles will often lead to a failed process. The second one is that it requires adopting design practices such as delaying decisions until enough information is known and extensive prototyping, which may seem pointless or a waste of resources [4]. Therefore, many researchers have worked on the integration of certain methods and tools to enable some activities of SBD [1]. For example, [13-17] use Trade-off Curves for design mapping based on information obtained from extensive prototyping to make decisions to find optimal solutions. In [12,18-20], Fuzzy Sets are used to define a design space while delaying decisions to achieve preferred designs. Also, some researchers have worked on integrating methods without purposing them for SBD. References [21-23] use Causal Mapping to generate Trade-off Curves with the intention of making design decisions, but do not explicitly approach problems from a SBD perspective.

Up to now, little attention has been paid to the development of roadmaps combining different techniques to enable SBD, going from a design concept to a design proposal. For this reason, here are listed four methods and tools that guide the designer in the process of handling different parameters, variables, equations, and interactions while dealing with uncertainty, feasibility, and preference. The following subsections describe each method and tool, and how they are integrated. Fig. 1 depicts the roadmap.

A. *GFIS Method for Problem Statement*

The GFIS [9] is a method that helps the designer to easily identify what information is known, which parameters and variables need to be assumed or calculated, what are the restrictions and preferences given by a problem. This method is formed by four sections:

- Given: lists the known and assumed information.
- Find: lists the unknown information.
- In Order To: lists the Functional Requirements that must be satisfied.
- Subjected To: lists specifications for design parameters and governing equations.

The design quantities present in the problem description are classified based on the definitions provided by [24,25] and adaptations from [9]:

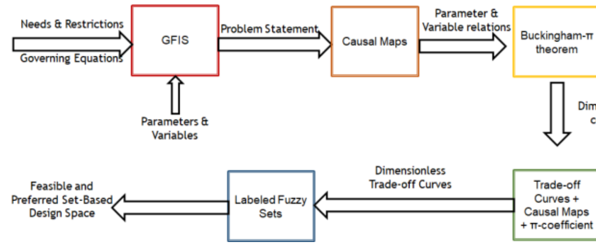

Figure 1. Roadmap of methods and tools to enable SBD.

- Design Parameter: "Any free or independent parameter whose values are determined during the design process".
- Performance Parameter/Variable: "Any parameter/variable used in the design process that has a specified value (Functional Requirement) determined independent of the design process. They are usually dependent on the Design Parameters, and possibly some other Performance Parameters".
- Output Parameter/Variable: "Any parameter/variable used in the design process that is dependent on the Design Parameters, and possibly some Performance Parameters, but has no specified Functional Requirement value".

It must be noted that there is a difference between parameter and variable. Parameters are design quantities that are fixed at manufacture while variables are design quantities that can change during operation.

The GFIS method sorts the information contained in the problem description, highlighting the needs, restrictions, and governing equations to return a problem statement with categorized design quantities. The organized information facilitates linking the elements present in a causal map.

B. *Nondimensionalization with Causal Mapping*

Nondimensionalization with Causal Mapping [10] is a technique based on the works of [21-23] but oriented to systematically generate dimensionless coefficients using the Buckingham-Pi theorem [26]. The first step for this technique is to draw a causal map of the problem. The instructions are the following:

- Place Performance Parameters/Variables to the left of the diagram.
- Place the Design Parameters and Output Parameters/Variables that directly influence Performance Parameters/Variables immediately to the right.
- Draw arrows between quantities that are related and indicate proportional relationships with a "+" sign and inverse relationships with a "-" sign. If there is a qualitative variable, no sign is added.
- Continue adding design quantities in this fashion until all of them are allocated.

After drawing the causal map, the method of dimensions for Buckingham-Pi theorem is applied. Cimbala [27] provides a set of recommendations to choose repeating variables. Using the information from the causal map, it is suggested to select quantities that are on the right of the map and have more interactions (more arrows going to the left), while it is forbidden to pick performance parameters/variables. Once the repeating variables are selected, dimensionless Π-coefficients are generated and substituted in the governing equations to nondimensionalize the mathematical models of the problem.

The final step is to draw another causal map where the Π-coefficients are influenced by the design quantities of the problem. The interactions can be deduced by looking at the dimensionless equations. This nondimensionalized causal map gives the relationships required to develop trade-off curves, which will be explained in the following subsection.

C. *Dimensionless Trade-off Curves*

Dimensionless Trade-off Curves [11] are a tool that depict the design space in terms of dimensionless Π-coefficients and the design quantities that influence them. The process to generate the Dimensionless Trade-off Curves is similar to the one used by [21,22], locating clusters of related quantities and Π-coefficients on the nondimensionalized causal map and plotting the equations that involve them. Then, the charts are linked to each other depending on common variables or common equations, as it is seen in the causal map. This way, the data obtained from one plot can serve to gather more information for the next plot.

Once the Dimensionless Trade-off Curves are generated, they will serve to visualize the feasible and preferred design space, which will be determined by using Labeled Fuzzy Sets.

D. *Labeled Fuzzy Sets*

Labeled Fuzzy Sets [12] is a method that combines Labeled Interval Calculus [28] to mathematically define sets of alternatives with the Method of Imprecision [29] to use fuzzy functions representing preference. The Labeled Fuzzy Sets are used to propagate the feasibility ranges that are listed in the *In Order To* and *Subjected To* sections of the GFIS method. Once they are determined, they can be plotted in Dimensionless Trade-off Curves to visualize the feasible design space. Then, using the fuzzy functions of preference, an optimized robust design can be achieved.

III. Band Brake Design Problem

A band brake consists of a rope, belt or a flexible steel band lined with a friction material. It is partially wrapped round the drum and its ends are connected to the lever [30], as it can be seen in Fig. 2. By applying a force at the end of the lever, the band gets tightened and due to friction developed between the band and the drum, the drum is brought to a stop [31]. The required equations to design a typical band brake are the following [32,33].

The braking torque M is given by:

$$M = r(F_1 - F_2) \tag{1}$$

Where r is the drum radius and F_1 and F_2 are the tensions in the band. The two tensions are related to each other by the

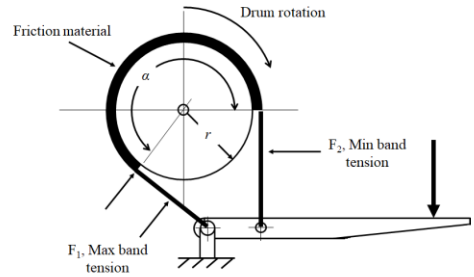

Figure 2. Band Brake schematic. Adapted from [33].

coefficient of friction between the brake lining and drum f and the angle of contact α. The relationship is:

$$F_1/F_2 = e^{f\alpha} \tag{2}$$

The point of maximum pressure p_{max} between the band and drum is at the point where F_1 comes into contact with the drum. Maximum pressure and F_1 are related as follows:

$$F_1 = rbp_{max} \tag{3}$$

Where b is the band width.

The problem presented by Gustafsson and Sobek [33] requires designing a band brake to exert a braking torque of 80 Nm. The designer will need to decide the lining material properties (f, p_{max}), drum radius (r), angle of band coverage (α), and band width (b). The braking torque must be within about ±5% of the 80 Nm target. The lining material is expected to be a woven material of some kind, whose coefficients of friction range from 0.25 to 0.45 and maximum allowable pressure of 350 kPa. For safety reasons it is preferred that this value is around 315 kPa, and any design with a value less than 280 kPa will be considered over-estimated and unacceptable.

A. *GFIS Method for Problem Statement*

Using the GFIS Problem Statement for Set-Based Design, it can be noticed that there are three *Given* design quantities and five *Find* design quantities. Since there are only three governing equations, it is required to assume two design quantities to be able to solve the equations system. For this exercise, the angle of coverage α is assumed to be between 210° and 330°, and the band width b is assumed to be between 1.0 cm and 3.0 cm. Reading the description, it can be deducted that the most preferred values for the Performance Parameters are M = 80 Nm and p_{max} = 315 kPa. Therefore, the fuzzy functions of preference must take these values into account. The problem can be stated as follows:

- Given: f, α, b, M, p_{max}
- Find: r, F_1, F_2
- In Order To: Maximize $\mu_1 = -0.25|M-80|+1$
  Maximize $\mu_2 = -|p_{max}-315|/35+1$
- Subjected To: $0.25 \le f \le 0.45$ $\quad 76 \le M \le 84$
  $210 \le \alpha \le 330$ $\quad 280 \le p_{max} \le 350$
  $1.0 \le b \le 3.0$ $\quad M = r(F_1-F_2)$
  $F_1/F_2 = e^{f\alpha}$ $\quad F_1 = rbp_{max}$

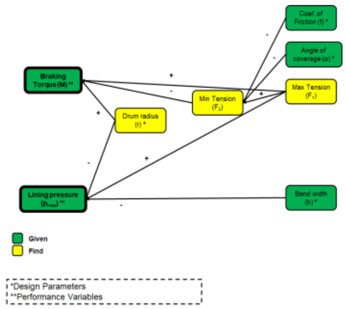

Figure 3. Causal map for a band brake [10].

The categorization of design quantities is the next one:

- Design Parameter: f, α, b, r
- Performance Parameter/Variable: M, p_{max}
- Output Parameter/Variable: F_1, F_2

With this information, the next step is to form nondimensional causal maps.

B. Nondimensionalization with Causal Mapping

Looking at the classification of design quantities, M and p_{max} would be placed to the left of the causal map. Analyzing M, it is "positively" influenced by F_1 and r and "negatively" influenced by F_2, as described in (1). F_2 is "positively" influenced by F_1 and "negatively" influenced by f and α, as seen in (2). Analyzing p_{max}, it is "positively" influenced by F_1 and "negatively" influenced by r and b, as depicted in (3). The resulting map is represented in Fig. 3.

The causal map is decomposed into two sub-causal maps, as Fig. 4 shows. Each sub-causal map is used for a separate dimensional analysis. The repeating variables used to generate Π-coefficients are r and F_1. The resulting coefficients are listed in Table 1.

The nondimensionalization of (1) is:

$$\prod_1 + \prod_2 = 1 \qquad (4)$$

The nondimensionalization of (2) is:

$$\prod_2 = e^{-f\alpha} \qquad (5)$$

The nondimensionalization of (3) is:

$$\prod_3 \prod_4 = 1 \qquad (6)$$

A combination of (4) and (5) results in:

$$\prod_1 = 1 - e^{-f\alpha} \qquad (7)$$

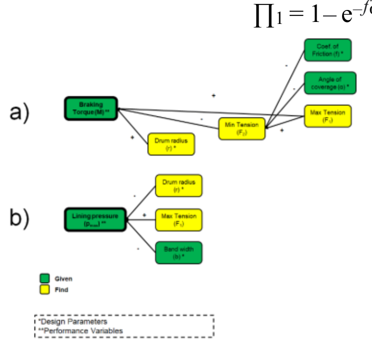

Figure 4. Sub-causal maps for a) Braking torque and b) Lining pressure [10].

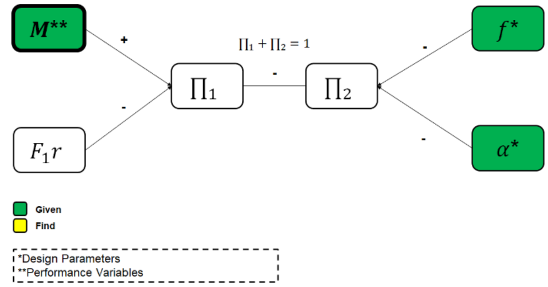

Figure 5. Sub-causal map for dimensionless coefficients Π_1 and Π_2 [10].

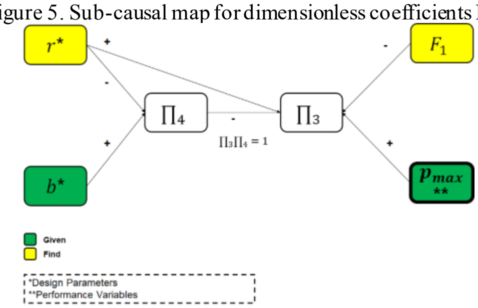

Figure 6. Sub-causal map for dimensionless coefficients Π_3 and Π_4 [10].

Using the nondimensionalized equations, a new causal map is generated following the same rules as with the first one. $\prod_2$ is "negatively" influenced by f and α, as seen in (5). According to its definition in Table 1, $\prod_1$ is "positively" influenced by M and "negatively" influenced by F_1r. Based on (4), $\prod_1$ is "negatively" influenced by $\prod_2$, and vice-versa.

TABLE I. LIST OF DIMENSIONLESS COEFFICIENTS GENERATED [10].

Sub-system "a" **M, r, F₁, F₂, f, α**	Sub-system "b" **p_{max}, r, F₁, b**
$\prod_1 = M/F_1r$	$\prod_3 = r^2 p_{max}/F_1$
$\prod_2 = F_2/F_1$	$\prod_4 = b/r$

These relationships can be described by the sub-causal map depicted in Fig. 5. According to its definition in Table 1, dimensionless coefficient $\prod_4$ is "positively" influenced by b and "negatively" influenced by r. According to its definition, dimensionless coefficient $\prod_3$ is "positively" influenced by r and p_{max}, and "negatively" influenced by F_1.

Based on (6), $\prod_3$ is "negatively" influenced by $\prod_4$ and vice-versa. These relationships can be described by the sub-causal map depicted in Fig. 6.

To link both sub-causal maps into a single one, an algebraic manipulation must be made to express $\prod_3$ in terms of F_1r. The resulting expression is:

$$\prod_3/r^3 = p_{max}/F_1r \qquad (8)$$

And to express $\prod_3/r^3$ in terms of b and r:

$$\prod_3/r^3 = 1/br^2 \qquad (9)$$

With this change, a nondimensionalized causal map is formed, as depicted in Fig. 7, and it can be used to start generating Dimensionless Trade-off Curves.

C. Dimensionless Trade-off Curves

Four clusters of design quantities can be identified in the causal map, one for each Π-coefficient. By writing $\prod_2$ in terms of $\prod_1$, and $\prod_4$ in terms of $\prod_3$, the clusters can be simplified as

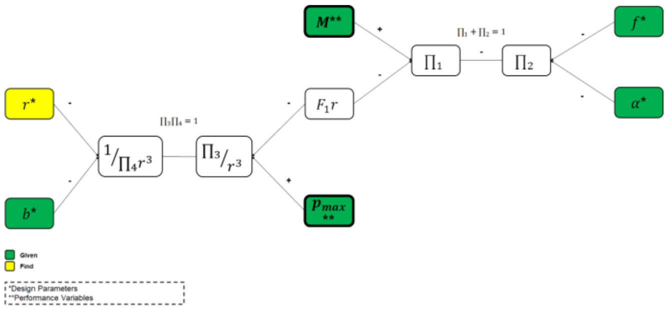

Figure 7. Causal map based on the nondimensionalized model [10].

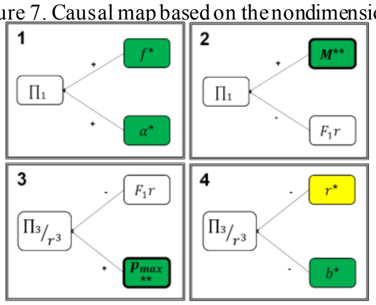

Figure 8. Clusters of dimensionless coefficients and their related quantities [11].

seen in Fig. 8. Each cluster is associated with a trade-off curve. Cluster 1 plots (7) to obtain $\prod_1$. Cluster 2 plots F_1r by using the Functional Requirement for M and the obtained $\prod_1$. Cluster 3 plots (8) $\prod_3/r^3$ by using the Functional Requirement for p_{max} and the obtained F_1r.

Cluster 4 plots (9) and is used to calculate r with the obtained $\prod_3/r^3$ and selecting values for b. With these Dimensionless Trade-off Curves, now it is possible to start drawing the feasible design space.

D. Labeled Fuzzy Sets

The RANGE operation [28] is used to propagate the feasible design space from one trade-off curve to another. This operation consists in taking an implicit equation in 3 variables (x, y, z) and a pair of intervals in 2 of the variables (x, y) to return the compatible interval in the 3rd variable, resulting in at least one combination of x and y that satisfies z. Fig. 9 to Fig. 12 illustrate the feasible design zone for this problem.

For cluster 1, RANGE operation is applied using the specified intervals for f and α in the GFIS Problem Statement:

RANGE ($\prod_1 = 1 - e^{-f\alpha}$, ⟨$f$ 0.25 0.45⟩, ⟨α 210 330⟩)⟶⟨$\prod_1$ 0.60 0.93⟩

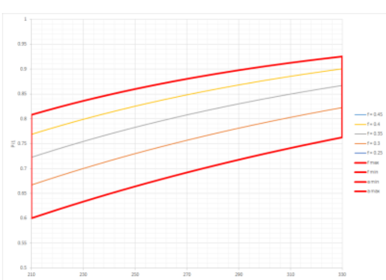

Figure 9. Trade-off Curve for Cluster 1 [11].

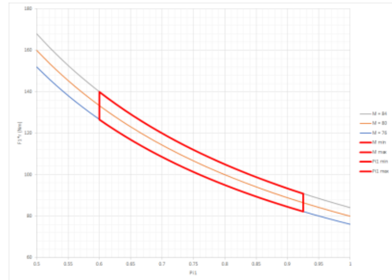

Figure 10. Trade-off Curve for Cluster 2 [11].

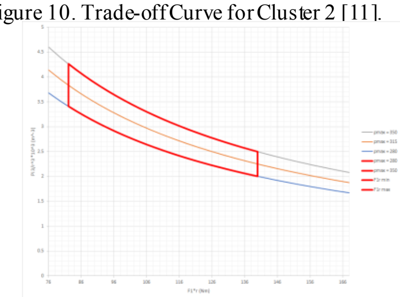

Figure 11. Trade-off Curve for Cluster 3 [11].

For cluster 2, RANGE operation is applied using the resultant interval for $\prod_1$ and the specified interval for M in the GFIS Problem Statement:

RANGE ($\prod_1$ = M/F_1r, ⟨$\prod_1$ 0.60 0.93⟩, ⟨M 76 84⟩)⟶⟨F_1r 82.2 140⟩

For cluster 3, RANGE operation is applied using the resultant interval for F_1r and the specified interval for p_{max} in the GFIS Problem Statement:

RANGE ($\prod_3/r^3 = p_{max}/F_1r$, ⟨$F_1r$ 82.2 140⟩, ⟨p_{max} 280 350⟩)⟶⟨$\prod_3/r^3$ 2.00 4.26⟩

For cluster 4, RANGE operation is applied using the resultant interval for $\prod_3/r^3$ and the specified interval for b in the GFIS Problem Statement:

RANGE ($\prod_3/r^3 = 1/br^2$), ⟨$\prod_3/r^3$ 2.00 4.26⟩, ⟨b 1.0 3.0⟩)⟶⟨r 0.09 0.22⟩

After propagating the feasible intervals for each cluster, they can be plotted in the Dimensionless Trade-off Curves. By doing so, the feasible design space can be represented in visual form. To find the preferred solutions among the feasible ones, it is necessary to use the fuzzy functions of preference listed in the GFIS Problem Statement.

The maximum preference is achieved when μ = 1. This means that the most preferred designs are the ones that can obtain a braking torque of M = 80 Nm and a lining pressure pmax = 315 kPa. Looking at the trade-off curves, there are many solutions. One example of an optimal solution according to the conditions of the problem is the following:

- Select f = 0.40 and α = 270°
- Substitute f and α in (7), obtaining $\prod_1 = 0.88$
- Assume M = 80 Nm and use $\prod_1$ to find F_1r = 90.9 Nm
- Assume p_{max} = 315 kPa and substitute F_1r in (8) to find $\prod_3/r^3 = 3.47 * 10^{-3}$ m^{-3}

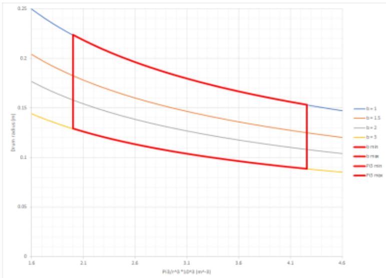

Figure 12. Trade-off Curve for Cluster 4 [12].

- Select b = 1.0 cm
- Substitute b and $\prod_3/r^3$ in (9) to calculate r = 0.17 m.

Once all the Design Parameters have been determined, a validation can be conducted to verify that the Functional Requirements are met.

IV. DISCUSSION

One of the main takeaways from the application of the proposed roadmap to the example is the provided systematic flow of information from the problem description to achieving a feasible and preferred solution. The integration of the methods and tools mentioned in the Introduction section contributed to enable SBD.

The GFIS method helped to make critical decisions at the earliest stages of development when there were many unknown Design Parameters and flexible assumptions had to be made to progress to further stages. The Nondimensionalization with Causal Mapping served as a platform to generate Dimensionless Trade-off Curves, which can be used for design space mapping and set-based exploration, while Labeled Fuzzy Sets contributed to set-narrowing. The use of visual resources such as causal maps and trade-off curves can be seen as a way to promote set-based communication since they can portray the interaction between many factors more intuitively than what a table with numbers or a set of equations can do.

This roadmap mainly focuses on problems with analytical solutions. It would be interesting to explore the challenges of adapting and expanding it to problems that require experimentation and/or numerical simulation to be solved.

V. CONCLUSION AND FUTURE WORK

While this roadmap still has plenty of room for improvement, it gives a broader scope on how to integrate different methods and tools to systematically enable SBD. The application presented in this work exemplifies the simplification of the design process by eliminating rework, and it should motivate other researchers to explore the integration of different techniques to formalize the principles of SBD that are widely discussed in the literature. Developing more complete roadmaps to facilitate the implementation of SBD is important in a world that requires fast innovation at a low cost to solve present and future challenges.

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