INTEGRATED IDEA GENERATION METHOD FOR CONCEPT GENERATION USING MORPHOLOGICAL AND OPTIONS MATRICES

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ABSTRACT
The use of morphological matrices in the generation of system concepts has two major limitations: a large number of combinatorial possibilities to explore, and a lack of guidance to generate design detail into concepts. An Integrated Idea Generation (IIG) method is proposed to generate system level conceptual ideas using a systematic combination of morphological matrices and instances of a focused idea generation tool (options matrix) to explore the design space through explicit innovation challenges. The IIG method is explained using an application in industry for the design of an automotive seat mechanism. Additional user studies and interviews, conducted in an institutional setting and in industry, suggest that IIG is a more complex and difficult method to use compared to a traditional morphological matrix method for concept generation. The results also indicate that IIG provides a link between high level concepts generated using morphological analysis and the generation of design details, is suitable for complex design tasks, and encourages innovative designs.

KEYWORDS
Morphological matrices, options matrices, concept generation

1. BACKGROUND AND OBJECTIVE
Conceptual design is one of the most significant stages that influence design of mechanical artifacts. In conceptual design, the functional specifications of a design problem are realized through physical representations having a high level of abstraction [1-3]. Design engineers identify the best design solution among competing alternatives that is most suited to the cause. However, despite the importance of exploring the design space thoroughly to identify the best solution, it is found that designers tend to focus on an initially identified solution without sufficiently exploring alternatives of innovative ideas [4]. They tend to modify an initial solution to counter its flaws, instead of looking for other alternatives [5]. Despite assertions that expert designers focus efforts to achieve long term cost-effectiveness rather than reduce short term cognitive cost [6], the problem of patching an original design solution (design fixation) still exists. Finger & Dixon stated that efforts should be focused on developing tools such as the morphological charts to enable designers to contemplate and consider design alternatives, resulting in better designs [7]. Design research has resulted in the generation of different methods and tools aimed to help design engineers identify an increasing number of alternatives. This is achieved through different types of problem decomposition techniques which foster idea generation [2] with a specific focus on functional decomposition [8-12], development of various intuitive idea generation techniques [13], creation of design repositories and other forms of knowledge sharing [14], and development of design alternatives through computer generated concepts [15].

The morphological matrix is a simple and powerful tool that enables a design engineer to organize and generate all the different alternatives before
identifying the best design solution [1] [16]. The morphological matrix typically consists of individual functional requirements of the system listed against potential ideas that can fulfill those functional requirements in a two dimensional matrix. A common representation of the morphological matrix is illustrated in Figure 1.

In Figure 1, the functional requirements are listed along the first column, and the ideas (means) are listed in rows pertaining to the specific functional requirements. A solution variant is generated using a morphological matrix by combining one of the means from each row of the matrix and integrating them into a single system. A system level conceptual solution is then generated by adding design detail to the solution variant such as development of interfaces, geometric layouts, and dimensioning.

![Figure 1 Generation of solution variants using morphological matrices (adapted from [1]).](image)

The major advantage of using a morphological matrix for concept generation is the ability to visually explore and evaluate the entire design space perceived by the designer. This is also a limitation of the morphological matrix tool as it presents a significant number of alternatives for consideration to identify the best design solution. For example, a design problem that is decomposed into five functional requirements with ten means identified to fulfill each functional requirement, can potentially present 105 (100,000) different combinations to consider. It is not possible to thoroughly explore all the potential ideas to identify the best concept.

Efforts have been made to overcome this problem through different quantitative techniques designed to transfer the cognitive load to computers and enable faster processing times [17-20]. The quantitative techniques are useful for design or redesign of systems with a highly focused design space, such as steering wheels [21], and do not lend themselves to design of mechanical systems like a vehicle seat mechanism where a number of components can interact in different ways to achieve the desired functionality. They require the definition of (a) large amount of design detail for each of the means identified, and (b) their interactions with other means, in order to compute the performance characteristics of the resulting system level concepts. The definition of such information to enable computation can be as laborious as an exhaustive evaluation of the design space by the designer. Also, as the means that are populated in the morphological matrices are typically at a high level of abstraction, the required information may not be readily available.

A second limitation of the morphological matrix tool in the generation of conceptual ideas is the lack of guidance on generating design detail to solution variants or the populated means. While modifications to the morphological matrices to support concept generation through qualitative analysis of the design space exists [22-24], they imply high level combinations of means without providing guidance on how to generate design details. It is asserted that relevant features of the design solution emerge through detailed analysis of the means, and that the design problem and solutions develop together [25]. It is also claimed that design is opportunistic in that the design direction is led by the knowledge that is gained from the analysis [25].

The purpose of this research is primarily to address the two major limitations of the morphological matrix as described using an Integrated Idea Generation (IIG) method, utilizing the morphological matrices and focused idea generation tools. The IIG method is developed to (a) facilitate an intelligent exploration of the design space without performing a full factorial exhaustive combination of means within a morphological matrix, (b) to systematically generate design details at various sub-system levels to generate detailed understanding of the design problem and the design space, and (c) to generate innovative design solutions.

The subsequent sections discuss the IIG method of concept generation using the example of the design of a seat chassis mechanism, outline some user feedback regarding the IIG method from novice designers and industry users (two user studies and six interviews), and conclude with a discussion of the
results of the user studies and interviews with a summary of the advantages and challenges associated with the IIG method and an outline of future work.

2. IIG METHOD OF CONCEPT GENERATION

2.1. Method overview

The Integrated Idea Generation (IIG) method is proposed to address the research questions identified in the previous section. Specifically, the IIG method aims to achieve the following objectives:

- Provide guidelines to a designer to systematically generate system level conceptual ideas from the individual means represented in a morphological matrix
- Generate design detail for generated concepts in order to exercise sound engineering judgment regarding their feasibility for the design task and facilitate a high level comparison against alternate concepts
- Reduce the number of combinations required to be performed by the designer in order to sufficiently explore the design space to generate system level concepts.

The IIG method is a systematic method of combining the means identified in a morphological matrix to form system level conceptual ideas. Therefore, in order to apply the IIG method, the designer must first perform the following three steps:

1. Perform a functional decomposition of the design task,
2. Generate ideas to fulfill the identified functions, and
3. List the identified functions against all the means generated to fulfill each function in a morphological matrix.

The basis of the IIG method is the generation of sub-system concepts through focused ideation on specific functional combinations within the identified functional decomposition of the design task. The IIG method is presented as a five step iterative process consisting of the following steps, as illustrated in Figure 2:

1. Grouping of the means within the morphological matrix
2. Generating ideas for each functional combination through focused ideation
3. Filtering of ideas for feasibility and comparison
4. Iteration to explore the design space
5. System concepts and options matrices

Figure 2 Overview of the Integrated Idea Generation method.
2. Preliminary filtering of the morphological matrix and identification of innovative means
3. Identification of functional combinations to perform focused ideation
4. Generation of sub-system concepts
5. Systematic integration of sub-system concepts to form system level concepts

2.2. Application of the IIG method in industry

The IIG method is explained with the example of a seat mechanism for an automotive application. The seat mechanism example was developed in collaboration with Johnson Controls Inc. (JCI) and hence, not all the information that was generated during the exercise can be entirely revealed to maintain confidentiality. JCI tasked a team at Clemson University to design a new seat mechanism for the driver and front passenger of an automobile that is cheaper than existing designs, and allows both manual and power-assisted seat adjustment.

The essential functionality of the seat mechanism is extracted out of the design task statement and the list of requirements, and stated as “Place an occupant in position”. The overall function is then decomposed into individual functions represented using a function list. The final functional decomposition represented using a function list is illustrated in Figure 3. A detailed explanation of the basis for the problem statement and functional decomposition is provided in [26].

Using the functional model displayed in Figure 3, seat chassis mechanism concepts are generated for the four functions and stored in a morphological matrix. The means contained in the initial morphological matrix are grouped into solution streams. A snippet of the grouped morphological matrix is illustrated in Figure 4.

In Figure 4, only some of the means that were generated for the morphological matrix and some of the solution streams that were used to group the means are illustrated, due to spatial constraints. Grouping the concepts into solutions streams proved to have three main advantages:

1. Generation of some additional means to certain solution streams that were not previously identified
2. Identification of and discussion regarding some of the means that are readily compatible with others and some of the specific advantages provided by those combinations
3. Identification of certain solution streams that were ‘weak’ because the majority of the means represented within the solution streams seemed infeasible.

<table>
<thead>
<tr>
<th>Function Model</th>
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<tr>
<td>1) Move along a trajectory with ±6°</td>
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<tr>
<td>2) Move vertical ±3° on trajectory path, “orthogonal”</td>
</tr>
<tr>
<td>3) Provide locking</td>
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![Figure 3 Illustration of the final functional decomposition of the design task.](image)

After the grouping of the means into solution streams, a preliminary filtering is performed on the means in the morphological matrix. During this process, each means represented on the morphological matrix is explained to the design team by the designer who generated each means. The team of designers then discusses each means, by generating additional details, generating the pros and cons of each means, and documenting the discussion within the concept sketch templates of the individual means.

Some of the means populated in the morphological matrix were clearly infeasible (marked using a red stop sign) with respect to the non-functional requirements and general considerations of cost, complexity, and other factors. For example, it was decided that using complex gear trains that allowed the motion along the required trajectory (F1) was not practical for use in automobiles due to space and cost constraints. Therefore, many of the geared 4 bar mechanisms were flagged as infeasible ideas for this design task.
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Additionally, some of the innovative means that were generated were flagged as interesting means to explore (marked using a black exclamation point). For example, the use of a horizontal track coupled with a driving and locking lead screw mechanism is prevalent in existing seat mechanisms. Since the lead screw mechanism offers specific advantages in a seating mechanism, a discussion on how the mechanism could be applied to a curved track ensued. By using a curved track and a lead screw mechanism to move and lock movement along the trajectory, and keeping the remaining mechanisms as it currently exists, it was possible to obtain a system concept not very unlike existing designs, despite being innovative.

Functional combinations are identified from the set of functions listed in the morphological matrix to perform a detailed analysis of the sub-systems that result from the combination. During this process, functions that seem to provide logical, innovative, or interesting sub-system concepts when coupled are identified.

Having identified the combination of the curved track and a lead screw to drive and lock the movement along the trajectory of the curved track, one of the functional combinations that were chosen to perform focused ideation was combination of functions [F1 and F4]. The functional combination of [F1 and F4] also provided the designers an opportunity to generate innovative power assisted movement mechanisms beyond the innovative combination of the lead screw and the curved track mechanism. The means within the morphological chart pertaining to functions F1 and F4 that are deemed to be the most promising in terms of generating innovative combinations are selected to carry forward to perform focused ideation in an options matrix. The selected means pertaining to functions F1 and F4 are populated in an options matrix as illustrated in Figure 5.

The combination of lead screw and the curved track was the main idea that was explored in detail. Three sub-system concepts resulted from the detailed analysis of how the two mechanisms could be combined.

The combination of the crank and track system with the lead screw results in concepts that are similar to the concepts generated for the combination of the curved track and the lead screw. The lead screw could not be combined in a practical or seemingly feasible manner with the double 4 bar linkage mechanism. Therefore, that particular combination is flagged as inconceivable at present. The potential for use of pneumatics with the movement mechanisms for a small vehicle application is limited and hence, not explored in detail.

The row of empty cells at the end of Figure 5 illustrate that the use of an electric motor to drive the movement mechanisms to fulfill F1 were not explored in this options matrix. This illustrates that some options matrices may not be completely populated before a designer diverts attention to a different combinatorial possibility using a different functional combination. Hence, the row of blank
cells as illustrated in Figure 5 represents a gap in the design space that has not been explored. This may happen when a designer is focused on trying to identify potential sub-systems with specific perspectives. For example, if a designer is focused on only identifying radical innovative sub-systems through combinations of non-obvious means, and staying away from using means existing within current designs, the potential for combining existing means with other means may not be explored until later in the design process to generate potential alternative designs.

As can be seen in Figure 5, an innovation challenge of non-structural is labeled along the top of the table. Various innovation challenges are used to explore different combinatorial possibilities and to serve as external stimuli to force designers to generate additional ideas. One of the innovation challenges used is the significance of designing the sub-systems as structural/non-structural units. The identification that all the sub-systems within the system need not be structural members came from a variety of different sources—during generation and discussion of combinatorial possibilities, questioning the domains of design knowledge leading up to concept generation (design task statement, list of requirements, functional model and the design space) with respect to TRIZ principles [27–28]. Based on the 40 TRIZ principles, questions can be asked of the different domains of design knowledge to generate innovation challenges. The questions are asked in a “what if” format. For example, “What happens to the combinations of two means if they were mechanically inverted?” is a question that can be asked based on the TRIZ principle of “The other way around”.

After the generation of the options matrix to explore the combination of F1 and F4, the resulting sub-system concepts are then integrated into a higher level (Level 2) morphological matrix. Since only one functional combination is used to explore the generation of possible sub-systems, only one functional module is contained within the level 2 morphological matrix as illustrated in Figure 6.

![Figure 6 Snippet of a level 2 morphological matrix.](image)

The level 2 morphological matrix (Figure 6) contains the remaining functions (F2 and F3) and their corresponding means duplicated from the level 1 morphological matrix because only one functional combination (F1 and F4) is used to generate sub-system concepts. Therefore the remaining functions and their corresponding means remain unchanged from the level 1 morphological matrix.

The function F2 is then combined with the functional module [F1 and F4]. This results in the coupling of the 4 bar mechanism with the lead screw driven curved tracks. As the sub-system concepts developed for the functional module [F1 and F4] are for a power-assisted movement mechanism driven by a lead screw, the potential for using a vertical actuator is also explored. However, the use of a 4 bar mechanism mounted on a curved track could draw direct parallels with existing seating mechanisms. Therefore, the use of a 4 bar mechanism is explored in conjunction with the sub-system concepts generated for the functional module [F1 and F4].

The use of locking mechanisms is then explored to identify how the 4 bar mechanism could be ideally controlled while enhancing the structural integrity of the system to cater to the crash load requirements that the design would be subjected to in real world applications.

As no feasible concepts could be initially identified, iteration through the process was necessary to identify additionally system level concepts. A number of potential functional combinations were explored and additional options matrices were generated in the search for system concepts. Although the IIG method proved to be helpful, it is important to identify if the proposed method can be easily employed by designers. Therefore, an analysis of the method’s usability was performed, as explained in the subsequent section.
3. USER STUDIES AND INTERVIEWS ON USERS OF IIG

In order to understand the usefulness of the IIG method and obtain feedback from novice and industry users, two user studies were conducted followed by six interviews. The user studies were conducted on undergraduate and graduate students at Clemson University and the interviews were conducted with graduate students and industry users. The interviews were conducted to obtain a more qualitative and direct feedback from the users than would be possible using user studies. No personally identifiable information was collected during the user studies or interviews to maintain anonymity.

3.1. Design of user studies

Two different design problems were given to two sets of users (See Table 1) with the information obtained from the first study used to refine the second study. A comparison was made between the IIG and the traditional use of the morphological matrix method of concept generation through the user studies. A detailed explanation of the design of the user studies are provided in [29] (in press).

For both the user studies, a twenty minute presentation was given to the participants explaining the use of the IIG method or the morphological matrix method. The groups that were tasked with using the traditional morphological matrix method were not exposed to the IIG method. Each student was provided with the following documents for each study (hard copies):

- A copy of the presentation
- List of requirements (single page)
- Function model containing the individual functions that the system was required to perform with the explanations of these functions also provided (single page)
- Morphological chart containing the individual functions and means to fulfill each function.
- Templates for the participants to draw sketches (both sections) and blank templates for options matrices and higher level morphological charts (for IIG method group only).

The design of the second user study was modified to take into account some of the challenges encountered during the execution of the first user study. First, it was found that using a fixed time slot to perform the user study placed the students under time pressure.

<table>
<thead>
<tr>
<th>Table 1 Differences between user studies</th>
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<tbody>
<tr>
<td><strong>User Study 1</strong></td>
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<tr>
<td><strong>Objective</strong></td>
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<tr>
<td><strong>Participants</strong></td>
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<tr>
<td><strong>Design task</strong></td>
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<td><strong>Design of study</strong></td>
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that could potentially affect the results of the study. This resulted in the decision to allow the students to perform the study at a time and location of their convenience, thus alleviating the problem of time pressure. Secondly, the users stated that an increased amount of time was required to sketch their ideas appropriately. Therefore, the duration of sketching was increased to 90 consecutive minutes with the provision of a 5 minute break to be used at the participant’s discretion. Lastly, it was found that the concept of using innovation challenges were ignored by the participants of the first user study, as there was a large amount of information provided to the participants and a relatively short duration of time was allowed to process the information and sketch their ideas. Hence, the concept of using innovation challenges was removed from the second user study. The use of innovation challenges in the first user study was also extended to the users of the morphological matrix method to provide parity of information content with the users of IIG method.

The resulting sketches from both the user studies were analyzed by two independent raters and ranked using a 1-3-9 scale on two metrics – quality of concept and level of design detail. After each rater evaluated the sketches independently, the results were compared. When differences in rankings were found, they were discussed and a corrected ranking acceptable to both raters were provided for each metric. The two metrics were defined as follows:

**Quality**: Defined as the ability of a concept to fulfill the functional and non-functional requirements. The measure of quality is based on the feasibility of the concepts, ranked on a 1-3-9 scale.

**Quality ranking**:

1 **(Low)** - Concepts that do not meet the functional or non-functional requirements without major modifications that may involve redesign of a significant number of components;

3 **(Medium)** - Concepts that seem to meet functional and non-functional requirements with some modifications or additional development, having some development of interfaces between components;

9 **(High)** - Concepts that potentially meet the functional and non-functional requirements, have specific advantages or desirable characteristics, and show a clear development and discussion of interfaces, components, and interactions.

**Level of design detail**: The level of design detail of the concepts that allows a designer to make informed decisions about potential feasibility or near-feasibility of a concept with respect to functional and non-functional requirements. The level of detail is measured based on the ability of a designer to decide on the feasibility of the concepts, ranked on a 1-3-9 scale.

**Level of design detail ranking**:

1 **(Low)** - Line diagrams or replicas of the ideas represented in the morphological chart with little development of layouts, discussion or representation of interfaces, or specific advantages and disadvantages;

3 **(Medium)** - Sketches depicting physical prototypes with some advanced development of geometric combinations, discussion or representations of interfaces between components, some discussion regarding geometry and functionality of components as would be in the final design;

9 **(High)** - Sufficient representation and discussion of geometry of components, use of materials, user inputs, interfaces and system functionality, enabling a designer to make a confident call on the feasibility of the concept individually and in comparison with other concepts.

<table>
<thead>
<tr>
<th>User Study</th>
<th>Metric</th>
<th>Agreement</th>
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<tbody>
<tr>
<td>1</td>
<td>Quality of concepts</td>
<td>81%</td>
</tr>
<tr>
<td></td>
<td>Level of design detail of concepts</td>
<td>95%</td>
</tr>
<tr>
<td>2</td>
<td>Quality of concepts</td>
<td>71%</td>
</tr>
<tr>
<td></td>
<td>Level of design detail of concepts</td>
<td>79%</td>
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### 3.2. Interviews with users of IIG and morphological matrix methods

Six interviews were conducted with users of IIG and morphological matrix methods. Two interviews each were conducted with novice users of morphological matrices, novice users of IIG, and industry experts who used IIG method.

The interviews were conducted for approximately 30 minutes with each user and they were asked to provide their views on the specific advantages and challenges associated with the method they used. The results of the interview provided some clarification on the results obtained from the user studies.
### 3.3. Conclusions from the interviews

For both the user studies, the confidence of the raters in the assessment of the perceived quality of the systems was significantly affected by the level of design detail of the concepts. While the design intent was clearly communicated in some sketches, it was not apparent in all cases, making it difficult for the raters to assess their quality.

The IIG method is more difficult to understand and implement compared to the morphological matrix method. The IIG users did not tend to combine functions that seemed to provide significant advantages in generating feasible concepts. It was also observed during the first study that the users requested clarification of the IIG method with the facilitator whereas the morphological matrix method was straightforward to use.

The results of the user studies cannot be used to establish a fair comparison between the morphological matrix method of concept generation and the IIG method.

### 3.4. Conclusions from interviews

The morphological matrix method is a simple, powerful and easy to use method for novice designers, and is suitable for simple design problems where users can visualize a system level concept easily. The IIG method is more suited to the designers in industry who focus more on the generation of finer details as well as those who focus on the smaller subsets of a complex problem to gain a deeper understanding of the system.

The users of the morphological matrix method are not always aware that the functions listed in a morphological matrix may not be hierarchical or sequential, and that changing the order of combinations of functions or means can significantly affect the concepts generated.

The IIG method is particularly useful where systems have key functions that require design and development. The IIG method also allows experienced designers to open their minds and explore concepts outside their paradigm. The usefulness of either method depends on the design task and the personal preference of the designers.

### 4. SUMMARY

The goal of the IIG method is not to propose an n-step algorithm or a prescriptive method of concept generation, but to emphasize the importance of generating knowledge of the system and developing innovative concepts through focused idea generation at the sub-system level, and to provide a platform for designers to achieve these aims. The IIG method is aimed to be open to interpretation and adapted to suit industry users without being overly demanding on time and resources, addressing concerns raised in [30]. It is also the intention of this method to support natural intelligence in the design of artifacts as discussed in [25].

The IIG helps to increase the novelty of the concepts generated through the structured use of innovation.
challenges, which are designed to identify implicit assumptions and foster creative ideas.

Fundamentally, the IIG method aims to emphasize the advantage of systematic, step-by-step integration of sub-system components into system concepts. This results in the development of knowledge about the design task and the design space, facilitating intelligent exploitation and exploration of the design space in the search for creative design solutions. While the user studies and interviews did not conclude that the IIG method generates greater design detail compared to the morphological matrix method, the feedback from the users suggests that the IIG method facilitates the generation of knowledge and design detail to an experienced user. It is also known that knowledge acquisition and control at different levels of abstraction are characteristics of creative systems [31].

The IIG method provides a structured approach in cases where designers need to focus on certain key functions. It especially helps in the redesign of systems where most of the information is well understood and innovative solutions depend on key functions or specific sub-systems that define the geometry of the system as a whole (for example, design of a power-assisted seating mechanism).

The IIG method provides a link between the high level system concepts and the generation of design details that is not addressed by the morphological matrix method. It allows the generation of concepts that are not immediately apparent in a morphological matrix.

One of the key aspects of the IIG method is the guided thinking that is encouraged in the search for conceptual ideas. Classification of the means into specific groups based on some rationale, selective focus on specific sub-systems or sub-functionality of the system, and the use of TRIZ principles to challenge your perceptions enable designers to navigate the design space and organize their thoughts in a structured manner. The IIG method also facilitates the formal documentation of the design directions explored, ideas that were pursued, rationale for ideas that were not pursued further, and identification of areas for innovation in future.

To summarize, the IIG method of concept generation is proposed to (a) facilitate an intelligent exploration of the design space without a full factorial combination of all the means in a morphological matrix, (b) facilitate the generation of greater design detail in the generation of conceptual ideas, and (c) foster the generation of creative design solutions. Although the IIG method has certain limitations such as increased complexity, greater time required to generate initial system concepts, and less intuitive use-ability than the morphological matrix method, the potential advantages of the method discussed herein make it a useful tool in conceptual design.

5. FUTURE WORK

Additional work is required to validate and expand upon the IIG method. The following tasks are being undertaken to build on the research:

- Validate the method using novice and experienced designers using a more formal method
- Develop software tools to support concept generation using IIG method
- Explore potential for use in different domains to make the method domain independent
- Teach the IIG method to designers and perform continuous assessment and refinement.

Some software tools are currently being explored that provide some support to designers in the use of the IIG method to generate concepts. This includes the use of existing resources such as design repositories and development of an ontological framework to support conceptual design using the IIG method.

ACKNOWLEDGMENTS

All acknowledgments for technical and financial support should be included in this section, which follows the text but precedes the references.

APPENDICES

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REFERENCES


