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O. Shai · Y. Reich

Infused design. II. Practice

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Abstract Infused design, introduced in the preceding paper, is a new methodology for design that opens up new channels of cooperation between designers from different engineering fields. The methodology enables an engineer from one engineering field to infuse his designs with the knowledge and experience of an engineer from some other field. During the “infusion”, the knowledge of the designers ascends to a common mathematical meta-level, consisting of discrete mathematical models—called combinatorial representations, and then descends to other disciplinary domains. All the domains that can be reached in this fashion are candidates to export knowledge for infusion. This sequel paper is aimed at unfolding the practice of the theory from part I by demonstrating four scenarios dealing with various design activities. The design scenarios studied in this paper expose novel cooperation channels between mechanical and civil engineers, and between mechanical and electrical engineers. Further applications of the proposed approach, including the pedagogical advantages it offers, are thoroughly discussed.

Keywords Collaboration · Concurrent engineering · Creativity · Combinatorial representations · Graph theory

1 Introduction

Infused design creates opportunities for improving design practice by infusing knowledge from one discipline to another. Infused design could be explained or exposed in different perspectives. In Shai and Reich

(2004), we presented its theory (part I), in which we motivated infused design by its ability to expand the scope of collaborative design. In part I and in this paper, we motivate infused design by its ability to enhance new product developments. Infused design can also improve analysis. Moreover, it can lead us to better understanding of our basic disciplinary knowledge as shown in Shai and Reich (2004; Table 1). In part I, we also analyzed infused design in relation to other studies dealing with analogical design, systematic thinking, etc. We concluded that in contrast to previous approaches, infused design provides a sound mathematical basis for the transfer of knowledge between disciplines, could expand with reasonable effort to new domains, and includes a bootstrapping effect.

In part I, we put forward four provisions made possible through infused design:

1. Provide tighter integration between designers through better and deeper understanding of disciplinary concepts. In doing so, reduce effort in, or make more effective, the informal exchange of information between designers and others involved.
2. Support the transfer of technical expertise including the transfer of solution methods and the creation of new knowledge.
3. Provide a basis for disciplines remote from engineering to understand part of the engineering work and even contribute to it.
4. Provide a basis for more efficient managing of projects involving multidisciplinary integrated systems.

The examples in this paper demonstrate the capability of infused design for enhancing the competitiveness of organizations. They demonstrate the first two provisions.

We discuss issues that were brought up in part I through the examples: the fact that it is easy to select between competing paths (because of our present limited knowledge), and it is easy to execute. Specifically, the third example is executed step-by-step so that the complete process could be understood.

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2 Preview

Four hypothetical scenarios of infused design (where the first two describe the same case) are presented in order to show that in essence, applying infused design is reasonably simple, yet practically, very powerful. The four scenarios describe:

1. Enriching terminology through formal transformation between disciplines.
2. Transferring analysis knowledge between disciplines.
3. Employing the CRCR technique for designing a static system.
4. Employing the CCCR technique for designing a new product.

While the first scenario is intuitive and the second involves analysis and not synthesis, the second is shown to benefit from the transfer of solution methods between domains and their elaboration in the original domain. These scenarios are shown to demonstrate the support that infused design provides for diverse design activities. The cases discuss the engineers' activities but do not deal with the mathematical basis that supports the activities. To understand this, readers are referred to additional references (see Table 1, part I). We mainly focus on the synthesis part of design—the creation of products given desired specifications. The latter two examples deal with such complex synthesis problems that many engineers would find hard to solve. We have tested this informally with many experienced engineers and encourage readers to check this themselves. With infused design, the solutions are developed quite easily. We describe the two synthesis cases through hypothetical scenarios in order to provide different perspectives that enrich understanding the scope and benefits of infused design.

The following notation is used in the scenarios:

- t is a disciplinary terminology (e.g., a way to describe force, rod, connection, support, or area used in structural engineering);
- M is the type of the combinatorial representation that governs the creation of a model;
- m is a particular model;
- s is a solution to a problem;
- superscripts denote different types of models or representations;
- subscripts denote different sub-parts of a system.

3 Enriching terminology through formal transformation between disciplines

In a new product development scenario, there was a need to design a small beam for transmitting a force to two supports. In one meeting, the mechanical engineer wanted to share this problem with the electrical engineer

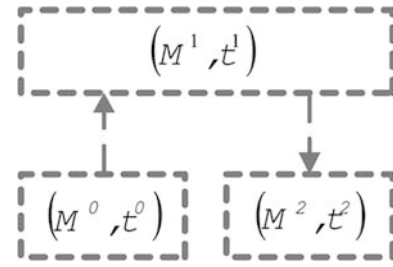


Fig. 1 Beam as a controlled system: relationships between representations

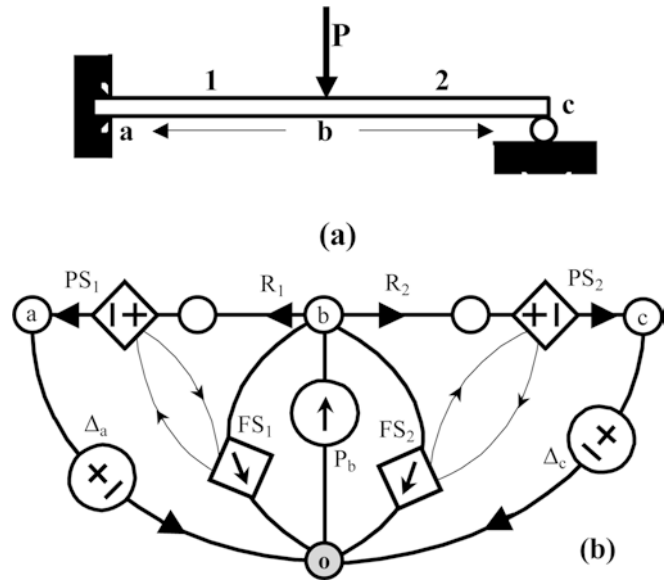


Fig. 2 **a** Beam skeletal structure, and **b** corresponding graph representation

and he¹ created two representations of the problem (Figs. 1 and 2): beam skeletal structure representation in (M^0, t^0) and a graph representation in (M^1, t^1) called “resistance graph representation” (RGR) (Ta’aseh and Shai 2002; Shai 2001c).

The mechanical engineer presented the electrical engineer with the domain representation (Fig. 2a) and its graph representation (Fig. 2b). Because of its simplicity, the electrical engineer could immediately observe that the graph, created in (M^1, t^1) corresponds with his own common modeling approach of electrical circuits (M^2, t^2) . Because the graph and its corresponding circuit are not complex, the engineer is able to identify the circuit as a controlled circuit. Viewing the static beam as if it were a controlled dynamic system enriches the mechanical engineer’s perspective and allows the electrical engineer to understand exactly the problem of his fellow worker, effectively demonstrating the first provision.

Such unforeseen correspondences between systems are characteristics of the early stages of infused design,

¹The terms “he” and “his” may equally refer to “she” and “her” or “they” and “their.”

in particular, in problem formulation. In traditional concurrent engineering, language evolves through various subjective informal means while in infused design, new terminology and concepts can arise from the formal process of translating between different representations including their terminology. Consequently, one of the outcomes of infused design is that it creates opportunities for semantic enrichment of vocabulary much beyond the important and critical process of aligning terminology in concurrent engineering.

In addition to terminology development, upon seeing the graph (Fig. 2b), the electrical engineer has provided the mechanical engineer with an advanced analysis method borrowed from electrical circuits. This idea is elaborated in the following section.

With the advent of support systems, the above association between a beam and a controlled system can be made available to other practitioners thus allowing them to share it and its consequences.

4 Transferring analysis knowledge between disciplines

Once the representation of the engineering system is established (Fig. 2), a mechanical engineer can reason over its behavior exclusively through the graph representation. Moreover, engineers from other fields, being presented with the same representation, are now capable of reasoning about this system as well and they can communicate at a deep level with each other. From the electrical engineer's perspective, the electrical circuit (Fig. 2b) seeks to maintain a requested balance between its left and right sides. The control properties of this circuit can be traced in the original structure as well, although they are not explicit. The behavior of the beam can be interpreted as follows: the forces and moments in the beam automatically adapt themselves to the external loads in such a manner that the deformations they produce in its two sides are equal at their mutual junction. Consequently, in accordance with his experience with control circuits, the electrical engineer suddenly enjoys the privilege of assisting the mechanical engineer in fulfilling tasks associated with the skeletal structure, such as making needed adjustments to optimize the structure performance. This new type of cooperation enables the electrical engineer to suggest an advanced method for analyzing the skeletal structures by employing his knowledge in electricity. In this hypothetical case, the electrical engineer suggested using the known "mixed variable method" (Balabanian and Bickart 1969), a method that has proven useful for extending further to multidimensional systems. The new method could then be applied successfully to analyze all types of skeletal structures (Ta'aseh and Shai 2002).

The benefit of infused design is much more significant than allowing the mutual analysis of systems by multidisciplinary teams as demonstrated in (Shai and Rubin 2003) where integrated systems were treated in a unified way without considering the engineering domain of each

element. The benefit extends to transferring analysis knowledge between domains, hence demonstrating the second provision. Once the engineering problem is represented by a combinatorial representation, then the embedded knowledge and the relations between the representations become available for solving the problem. This embedded knowledge includes methods and theorems, thus when different engineering systems are transformed into the same representation by changing their terminology, the same analysis methods can be applied for both systems. For example, when electrical circuits and indeterminate structures are represented by the same combinatorial representation, which in this case is the RGR, known analysis methods in these fields are revealed to be the same. For instance, the node method in electricity and the displacement method in structural mechanics were found to be special cases of the cutset method embedded in the representation (Shai 2001b). This idea was briefly mentioned in part I, Sect. 3.1 where an example of cooperation of type CCCR is used to transfer analysis methods between civil and electrical engineers.

The graph representations developed till now and the associated engineering systems form a highly interconnected system of channels for knowledge transfer both between the engineering domains and the graph representations, and between the graph representations and themselves. Figure 3 summarizes all the relations developed so far in a "hierarchic map" of different graph representations and engineering domains. The map comprises graph representations (designated by cubes to emphasize the existence of the embedded knowledge), engineering domains, and all their possible interrelations. Since the graph representations constitute a more abstract mathematical level, in the diagram they appear above the level of the engineering domains. Also, because some representations were found to be more general than others, they appear at different heights in the diagram.

Observing the map of Fig. 3, the engineer can comprehend a global perspective of the options newly opened to him through infused design. He can see in which engineering discipline to seek for collaboration in order to derive the most productive results. The network of relations constitutes the present search space for useful representations and domains. It is being extended continually through further research.

5 Employing the CRCR technique for designing a static system

Consider the following design problem: Design a static system, such that when a small force P is applied to one of its joints, a much greater force is produced in one of its rods (rod 1). Figure 4 shows a model of the problem m^0 , which is a result of interpreting the problem statement. The representation makes use of primitives from the physical model type M^0 . Once it is described using a

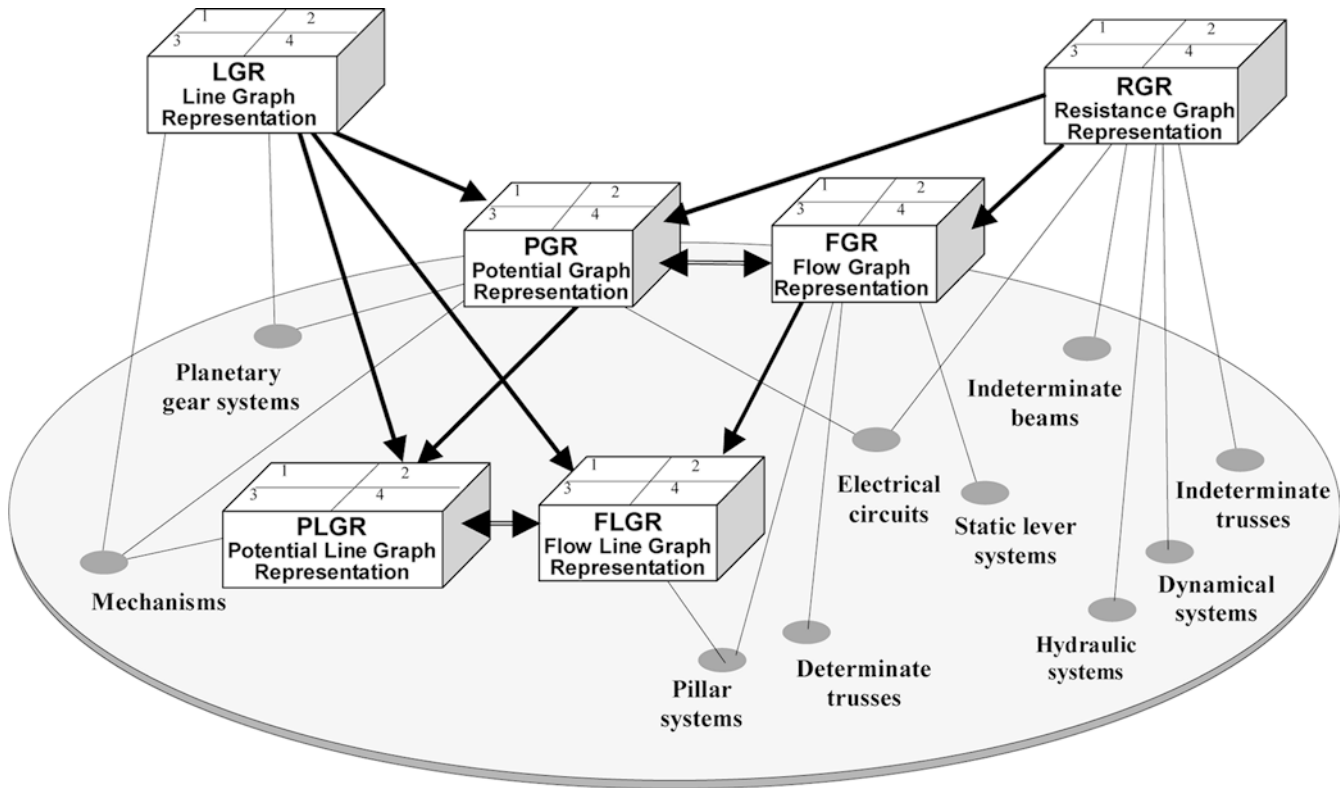


Fig. 3 Hierarchic map of graph representations, their interrelations, and association with engineering systems

particular terminology t^0 (force, rod, external forces, force equilibrium, etc.), it constitutes the problem representation.

5.1 General process description

In part I, Sect. 4, we described the process of infused design. We carefully reconstruct that process in this hypothetical case as shown in Fig. 5 (the numbers correspond to the numbers on the figure):

1. First, the terminology of the model type M^0 is altered from t^0 (force, rod, ...) to t^1 (flow, edge, flow source, flow laws, etc.), leading to a new model type M^1 of flow graph models (in flow graph representation—FGR). Figure 3 shows that the choice of FGR implicitly suggests that we are looking for a deter-

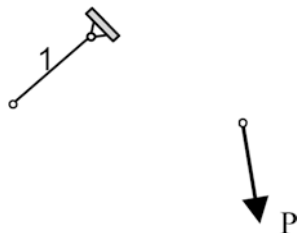


Fig. 4 Design problem—designing a static system for amplifying force

minate truss or a static lever system, even though an indeterminate truss can be equally viable.

2. The problem is articulated in the terminology and modeling primitives of a flow graph model: “design a system where the flow in one of the elements is highly amplified related to the flow in the flow source”.
3. At this level, representations can be transformed into dual representations, or through other graph relationships, into other representations. In our problem, the path can go to the dual potential graph representation (PGR) M^2 with its own terminology t^2 (potential difference, ...). As shown in Fig. 3, other options are the RGR that could lead to disciplines such as electrical circuits and the FLGR that leads to pillar systems. The reason to pick one representation over another is context dependent. For instance, the present design team includes a capable mechanical engineer knowledgeable about infused design. The choice of representation is such that this engineer can contribute to the process. This is a rather rudimentary reason. In other situations, the choice of representations involves experience in employing infused design. For example, we might encounter the need to check the stability of a system. In the static domain, this might be hard, but if we translate it into a different problem (e.g., by a dual transformation), it could be solvable (e.g., using the knowledge and methods in the dual engineering domain). The representation we will pick would be one that we know will lead to such a domain. The problem is translated into a new representation: “Design a system where

Fig. 5 Process of designing a static system for amplifying force through CRCR method

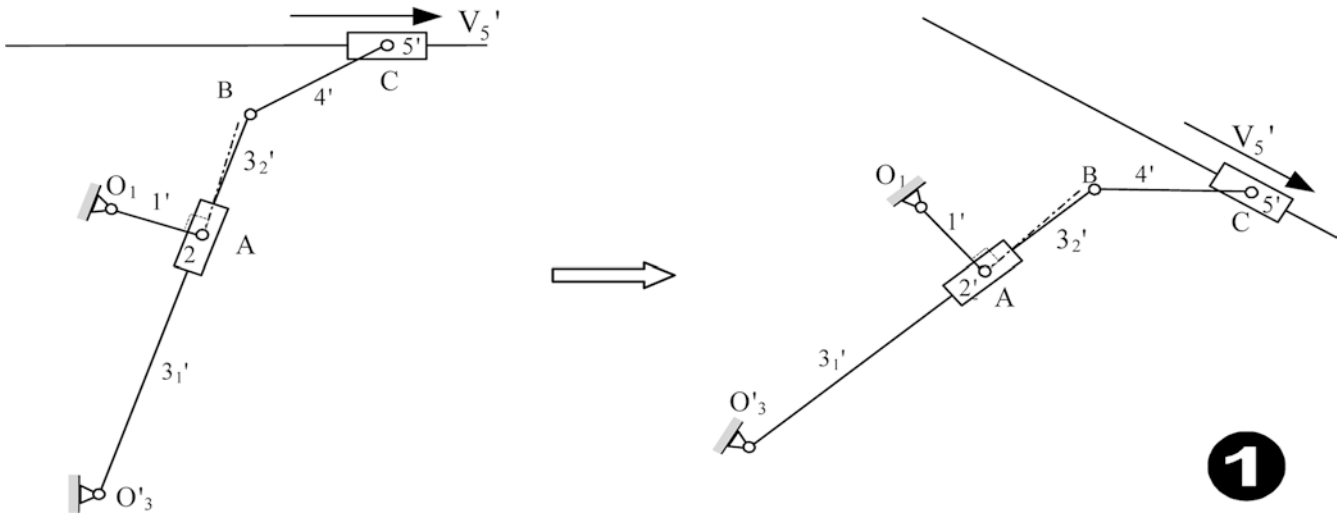


Fig. 6 Step 1—adjusting the velocity of link 1' to be in the direction required of the output rod

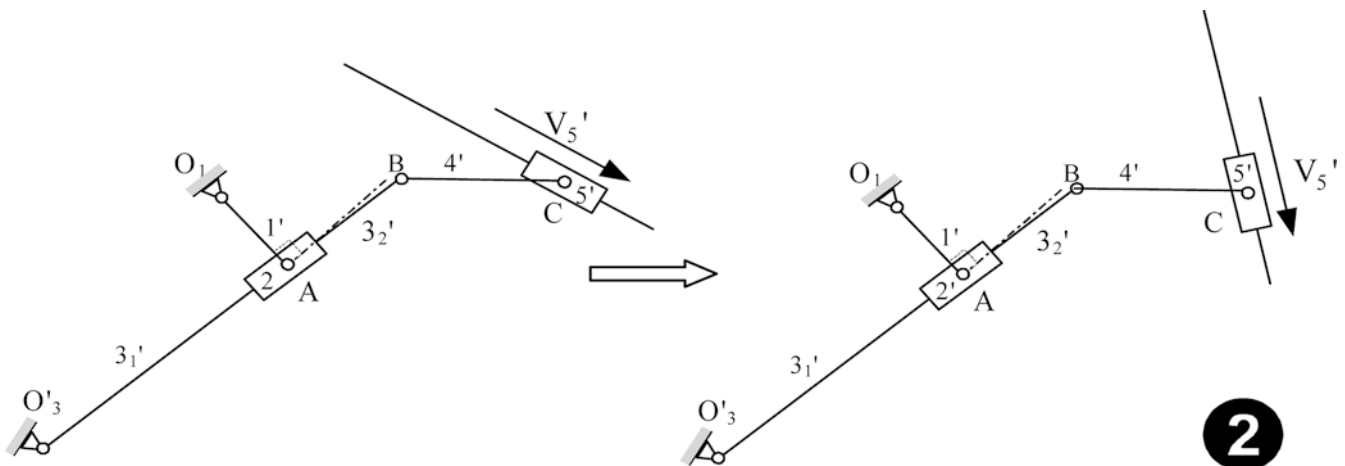
the potential difference in one of the elements is much higher than the potential in the potential source”.

4. The mechanical engineer changes the representation to that of mechanisms (M^3 , t^3). The terminology t^3 becomes: relative linear velocity, link, driving link, etc., and M^3 becomes the reference model of the original problem model M^0 .
5. The problem statement in this representation becomes: “Find a kinematical system such that the ratio between relative velocities of its two links is large”. This is a known problem in the mechanism community.
6. Given the numerous solutions to this problem in the literature, the mechanical engineer finds the problem to be easy. The mechanical engineer outlines several solutions that he considers to be valuable. He exercises his knowledge to select some or one promising solutions.

Fig. 7 Step 2—adjusting the mechanism position so that the velocity of the driving link (link 5') is oriented as required of the external force P

Up to this point, the infused design process had little input from the original problem, aside from the general functionality sought of the design. The next steps are much more detailed since they involve the adjustment of the particular solution retrieved and its systematic transformation between the different representations to result in a useful design solution. The selection of another kinematical system as a solution would have resulted in another static system through different transformations. We illustrate these steps with the assistance of Figs. 6, 7, 8, 9, 10, 11, 12, 13, and 14. The main idea of the steps appears next, while the detailed explanations of the figures appear in Sect. 5.2.

7. The selected solution is displayed. It is a “shaper mechanism” (Martin 1969). Once an existing design is retrieved, there is a question as to its resemblance to the original problem specification. In order to adjust the existing design in Fig. 5, step 7, the shaper mechanism is modified (Fig. 6, step 1 and Fig. 7, step 2) such that the direction of the velocities of the relevant mechanism elements (output link 1 and input link 5) are in the same direction as the direction of the bar element and the external force in the problem specification (see Fig. 4).



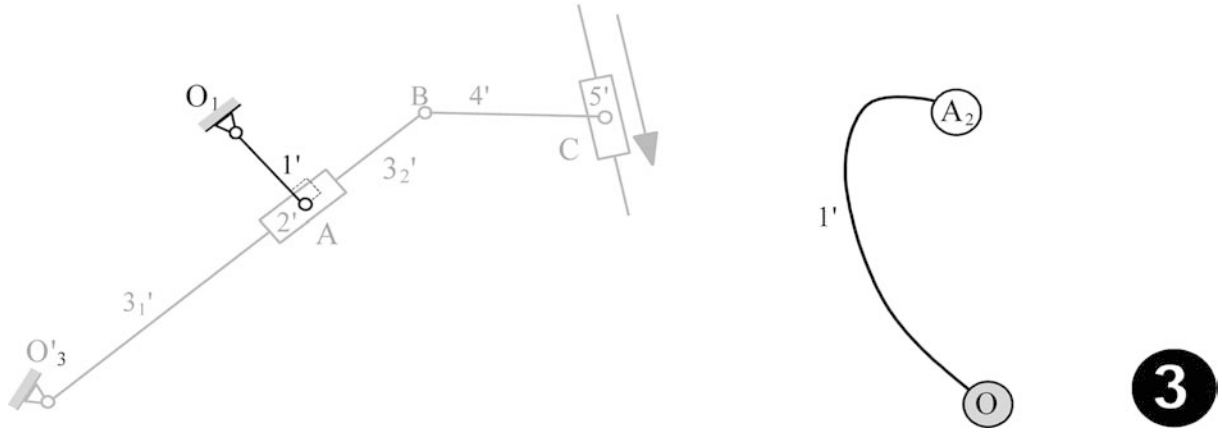


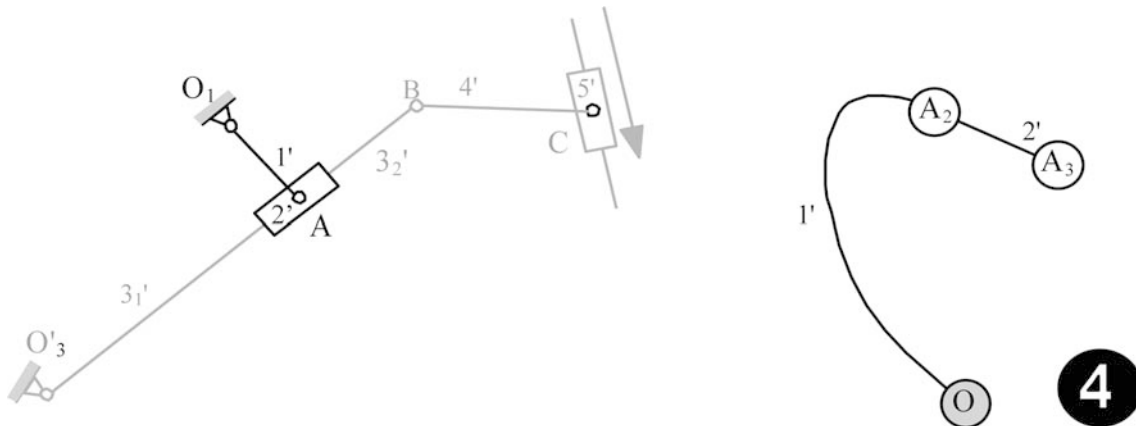
Fig. 8 Step 3—adding edge 1' to the graph representing link 1' (output link) in the mechanism

8. The terminology is changed back again to the PGR in order to map the solution through the opposite path to the original problem.
9. The adjusted solution is transformed again into the dual FGR. Figure 8 (step 3) to Fig. 12 (step 7) show how the mechanism is transformed, step-by-step, in a systematic manner into the PGR. Once the graph is constructed, its dual flow representation is constructed as shown in Fig. 13, step 8.
10. The final change occurs when the problem reaches its original representation through another terminology change.
11. The solution to the problem is finally obtained in the representation of a static system. Figure 14, steps 9–14, show in detail the construction of the static system from the dual graph representation. Because of the original solution adjustment, the final design is guaranteed to satisfy the requirements.

An abstract flow of the overall infused design process is

$$(m^0, t^0) \in (M^0, t^0) \rightarrow (M^1, t^1) \rightarrow (M^2, t^2) \rightarrow (M^3, t^3) \\ \rightarrow (m^3, t^3, s^3) \rightarrow (m^2, t^2, s^2) \rightarrow (m^1, t^1, s^1) \rightarrow (m^0, t^0, s^0).$$

Fig. 9 Step 4—adding edge 2' representing slider 2'



The sequence of steps transformed an original problem into another and was able to retrieve a solution to the problem with relative ease. Once explored, this path can be easily recalled in similar future situations.

5.2 Detailed explanations of transforming from the source to the target design

5.2.1 Adjusting the “shaper mechanism” according to the design requirements

The solution of the design problem in the secondary engineering field involves finding an existing system that solves the transformed problem in principle and adjusting it to the specific problem requirements. In our example, the engineering system in the secondary engineering domain—mechanisms, which performs the required velocity amplification, is the known “shaper mechanism.” The specific problem parameters to be met are the specific angles of the input and the output rods that in the dual problem transform into the angles of the driving and the output links. The mechanism should be adjusted while maintaining the main property of the mechanism—velocity amplification—unchanged.

We should first take care of the angle of the output rod, as depicted in Fig. 6. In order to do so, the angle of the output link in the shaper mechanism should be set to

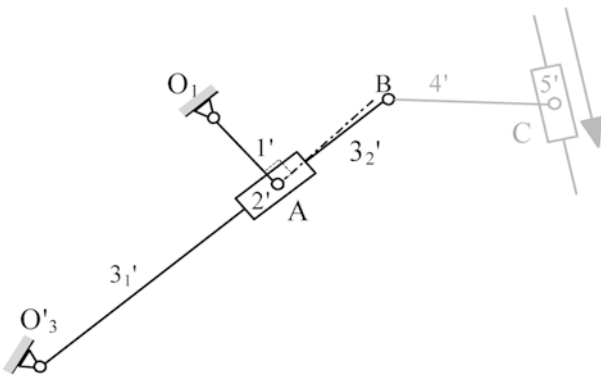


Fig. 10 Step 5—since link 3' possesses three joints it is represented by two dependent edges in the graph— $3_1'$ and $3_2'$

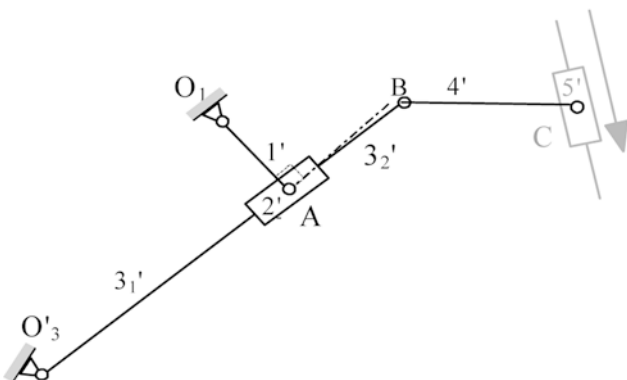
be perpendicular to the required rod angle. Step one shows a rotation of the whole mechanism to put link 1' in the required position. Since the mechanism was rotated as a whole, all the relative angles between its links remained the same, thus it still possesses the velocity amplification property.

In order to meet the requirement for the angle of the external force acting upon the truss to be found, the surface of sliding of the driving slider 5' should be set to be parallel to the required force. This is done in step 2 of the process (Fig. 7). The amplification property of the mechanism remains, since there is a component in the velocity of the slider that is parallel to its original velocity.

5.2.2 Constructing the potential graph representation of the mechanism

Once the final solution is obtained in the secondary engineering domain, it is transformed to the terminology

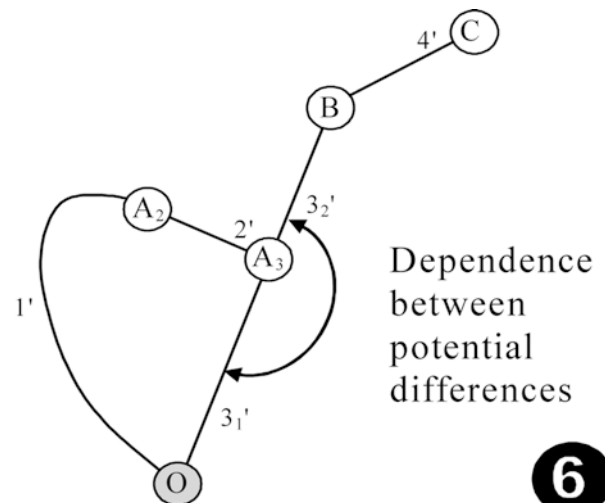
Fig. 11 Step 6—adding edge 4' representing link 4 in the mechanism



of its corresponding graph representation—the PGR. This is done in accordance with the construction rules associated with the representation: each link of the mechanism is represented with an edge in the graph and each joint is represented by a vertex. Each edge is associated with an angle of the relative velocity of the link it represents. Each vertex in the graph is associated with a vector variable, called “potential”, which is equal to the absolute velocity of the mechanism joint it represents. Similarly, each edge in the graph is associated with a vector variable called “potential difference” equal to the relative velocity of the corresponding link in the mechanism. Steps 3–7 show gradual building of the potential graph representation of the shaper mechanism. At each step, a single edge is added to the graph in accordance with the connection of the corresponding link in the mechanism.

Adding the edge corresponding to link 1' in the mechanism (Fig. 8). The end vertices of the new edge are named in accordance with the joints that connect link 1' to the mechanism. Since link 1' is the output link of the mechanism, edge 1' is the output link of the corresponding graph.

The slider 2' is represented by an edge 2' in the graph (Fig. 9). The slider is connected to the mechanism through two kinematical pairs both located at the same geomet-



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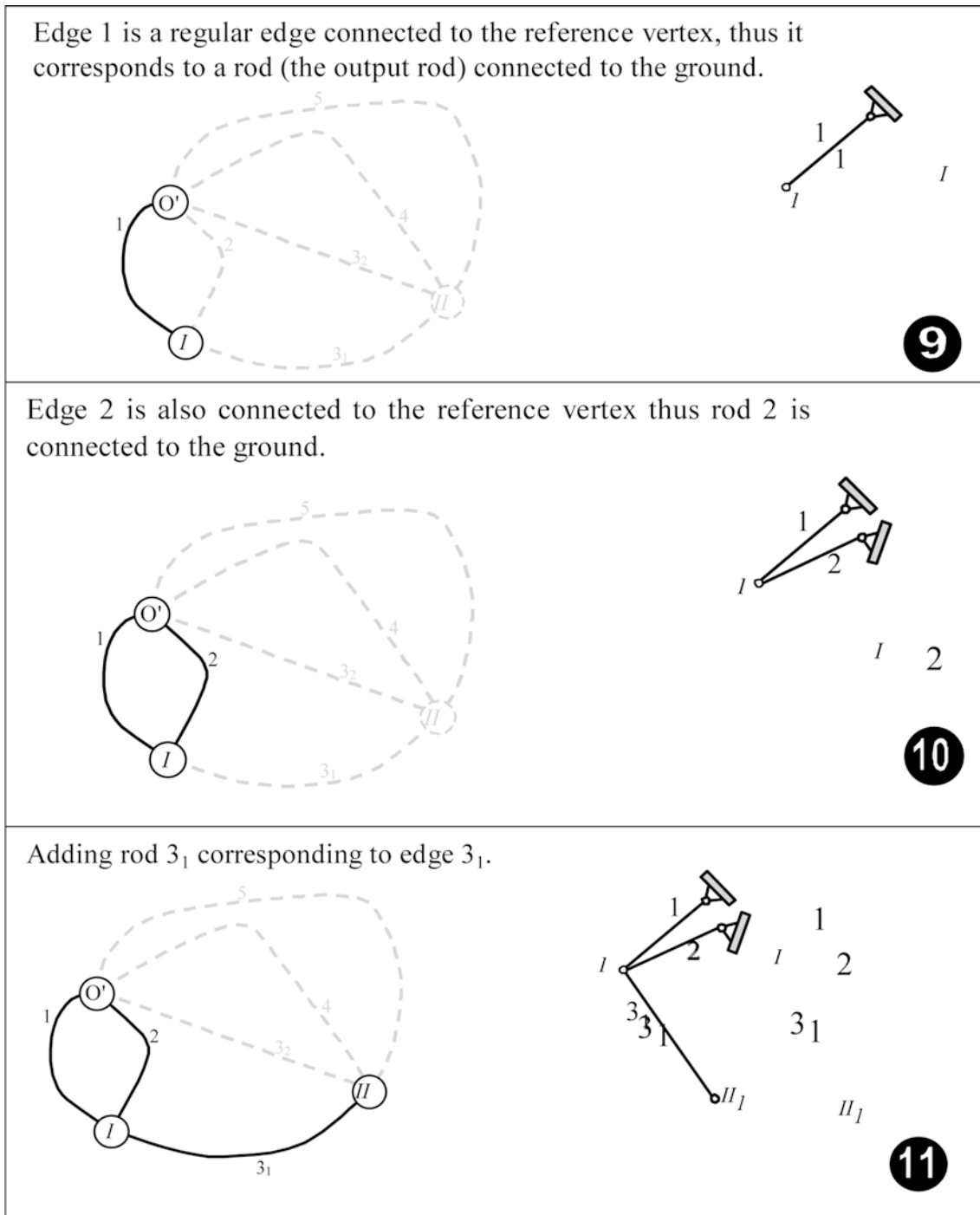


Fig. 14 Steps 9–14—detailed design steps for constructing a force amplifier from the corresponding FGR

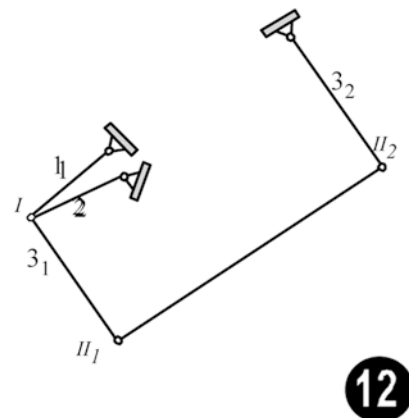
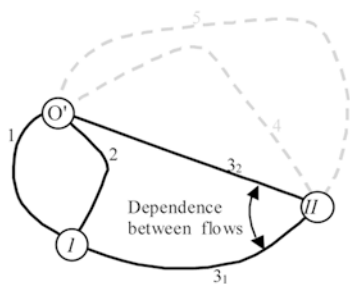
Edge 1 is connected between the common reference vertex of the graph and the vertex designated by I . Thus, the corresponding rod will be connected between a rigid support and some joint designated by I . It should be noted that because of the correspondence between the angles, rod 1 is perpendicular to link 1 in the shaper mechanism.

The truss obtained in step 14 is the final truss complying with the original design requirements.

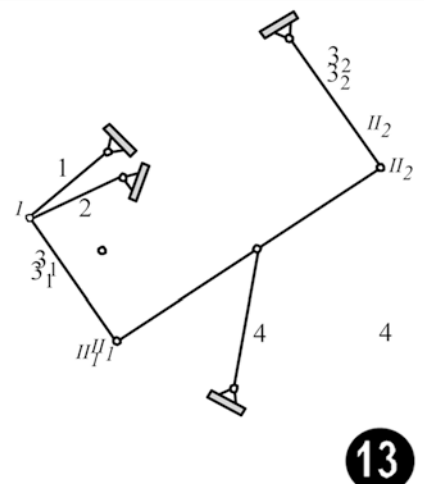
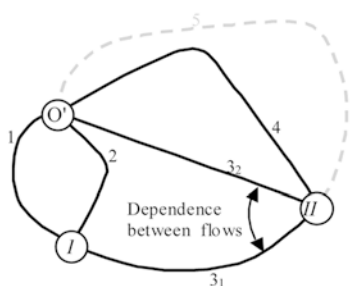
6 Employing the CCCR technique for designing a new product

As was explained in part I, Sect. 3.1, the CCCR enables transferring knowledge between engineers from diverse engineering fields through common combinatorial representations. This new channel of knowledge transfer paves a way to new types of cooperation between civil and electrical engineers where the latter helped the former to analyze an indeterminate truss by means of

Since edges 3_1 and 3_2 are dependent, the corresponding rod 3_2 is added with a lever.



Adding rod 4 corresponding to edge 4.



Edge 5 is a flow source edge corresponding to the external force P .

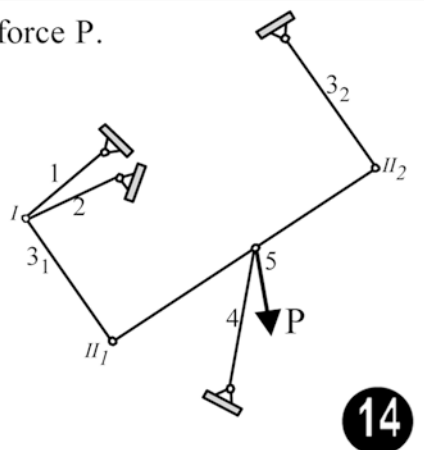
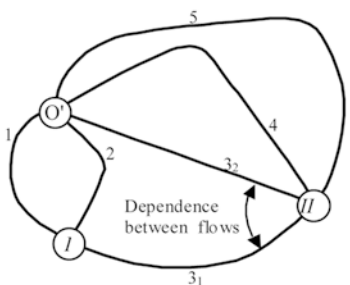


Fig. 14 (Contd.)

infusing methods from one domain into another. In this section, the scope of this type of cooperation is expanded to design.

In the given design case, the mechanical engineer is requested “to design a mechanism so that its driving link rotates alternatively in both directions while its output link rotates always in the same direction, but with the same value of angular velocity”, as shown in Fig. 15.

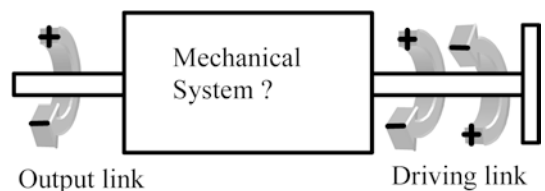


Fig. 15 Designing a mechanism without alternating output velocity direction

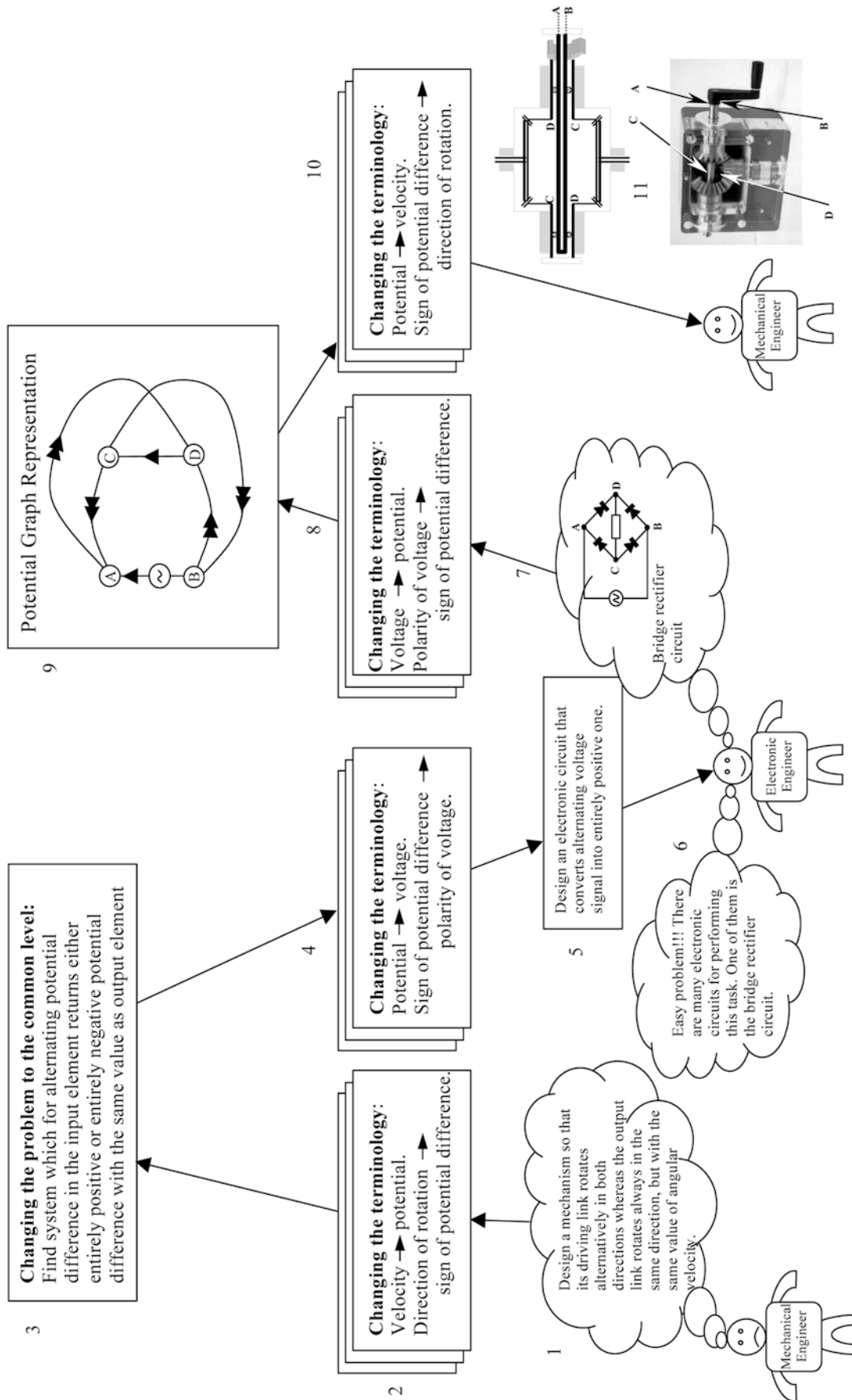


Fig. 16 Employing CCCR for designing a special gear system

In this design case, the mechanical engineer finds that his colleagues from the mechanics community cannot help him. Admittedly, this is a difficult design problem whose solution was only patented in 1999 (Marcovici 1999).

With present design practice, the mechanical engineer is left at an impasse with no alternative solution approach. His peers from different disciplines cannot offer any help. An electrical engineer could collaborate on the problem by designing, for example, a control unit, but such confined collaboration is conditioned on defining an interface between the mechanical and electrical subsystems and transferring parameters and constraints back and forth between the engineers. However, what good would a control unit do if the mechanical engineer does not know how to address the basic design problem?

In our hypothetical case, the mechanical engineer is familiar with infused design so he is aware of the new avenues of cooperation that are available to him. Thus, he applies for assistance to a colleague from a different engineering field, in this case electrical engineer. This new opportunity of cooperation is one of the main ideas behind infused design since it changes the nature of communication and cooperation between designers to an extended level than presently possible.

The infused design scenario is depicted in Fig. 16. The first phase in the infused design process is instituting a common language between the mechanical and electrical engineers. This is accomplished by applying steps 1 and 2 where the mechanical engineer changes the terminology of the mechanical problem to the terminology of a special combinatorial representation—PGR. At that level, the problem becomes:

Find a system that for alternating potential difference in the input element returns either entirely positive or entirely negative potential difference with the same value as output element.

This step raises the mechanical engineer's reasoning to the common combinatorial level (i.e., PGR) that possesses meta-knowledge about several engineering disciplines. Presently, according to Fig. 3, these disciplines are planetary gears, mechanisms, and electrical circuits. As both the mechanical and electrical engineers employ this representation, the obstacles to extended meaningful communication between them are abolished, rendering the disciplinary boundaries insignificant to quality knowledge communication—a sharp divergence with present concurrent or collaborative engineering practice where disciplinary knowledge does not cross disciplinary boundaries. The use of this representation allows infusing, concepts, methods, and solutions between these disciplines.

In steps 4–7, the electrical engineer transforms the problem into electrical circuit representation. In this domain, the problem is easy with numerous solutions available. The electrical engineer picks one of several classical rectifier solutions.

The solution is mapped back to the common combinatorial representation PGR (steps 8 and 9). (The

letters in the graph denote equivalent components as in the solution in step 7.) Subsequently, the solution is mapped from the PGR into the original domain (steps 10 and 11). There could be several ways to map the combinatorial representation entities into mechanical components. These ways could be catalogued in a design support system. The particular components are selected based on disciplinary experience. The prototype product resulting from a set of such choices is shown in step 11. The figure shows a model and a picture of the prototype—a replication of a product patented in 1999 (Marcovici 1999).

Clearly, this design problem is difficult. The patented solution and the difficulty faced by experienced engineers, attest to this observation. Nevertheless, the process that we described seems quite straightforward to use, leading to unexpected, potentially very creative, design solutions. This example further demonstrates that infused design expands the scope of present engineering practice and has far reaching consequences to design practice.

7 Conclusions

In the examples, we showed how the simultaneous use of multiple representations augments human thinking with previously unknown knowledge. We showed how by the mapping of different domains into a common ground, terminology from one discipline could augment that of the other, providing new perspectives for reasoning about familiar designs. We demonstrated an example of transferring solution methods between disciplines. Finally, we gave two examples of transferring solutions in one discipline into completely different disciplines and solve complex, non-trivial engineering problems. Such transfer in design has not been demonstrated before. One of these examples included a detailed step-by-step execution of infused design through all the mathematical manipulations.

Our experience in laboratory settings shows that infused design can be studied with reasonable effort. We have student that studied the methods and can apply them effectively. For example, electrical engineering students can now teach the concepts and behavior of mechanical systems such as beams to their peers. Other students have studied the methods and applied them successfully to propose novel solutions to design problems.

Several industries have shown interest in the two main directions related to using infused design. The first direction addresses teaching engineers that have to deal with topics from disciplines outside their main expertise. By adopting infused design techniques, engineers are able to learn mechanics through their knowledge in electronics, and vice versa. Another direction of interest is in the new devices that infused design has yielded and that have been constructed at the university laboratory. These products are based on new engineering concepts derived by the methods that even experienced engineers had difficulty in envisaging.

Clearly, infused design expands the scope of engineering practice, opening avenues for bootstrapping our understanding and supporting various design practices such as creative design. The bootstrapping effect comes from an interesting and non-trivial phenomenon of infused design. When we use infused design to perform design, we understand the underlying representation better. We can also uncover more properties of the representation that in turn, would improve our ability to do analysis. Subsequently, this can lead to yet better design ability. Because of its complexity, we leave the explanation of this phenomenon to a future study and only note its existence here.

We have illustrated infused design in the context of two knowledge transfer principles, CCCR and CRCR. However, infused design is not limited to these principles. We are continuing to elaborate the set of principles beyond those represented in Fig. 3 thus further expanding the scope of infused design.

Our presently limited knowledge depicted in Fig. 3 creates a manageable representation landscape—however, it is growing steadily. Even in its present form, it has already led to interesting results and opened avenues for many more applications with the present disciplines. As we progress, it will become highly useful to create infused design support systems that will assist in the process.

Meanwhile, we hope that the expected benefit of infused design will lead other researchers to join the effort and expand the landscape by introducing new disciplines.

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