GEMS of SAPPhIRE: A Framework for Designing?

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Abstract

This paper proposes a framework of designing for conceptual and early embodiment design that uses physical laws and effects explicitly as a central aspect for designing. This is especially important in domains that make explicit use of physical laws and effects in their design, such as novel sensors. The objectives of the paper are: (a) Develop a model, (b) Empirically evaluate the model and (c) Propose a framework. The model is developed by integrating the activity- and outcome-based elements. The model is validated empirically by analyzing protocols of design sessions to find instances of activities and outcomes. Based on the findings, a framework is proposed on how designing should be done. Elements of GEMS (**G**enerate-**E**valuate-**M**odify-**S**elect) and SAPPhIRE (**S**tate change-**A**ction-**P**art-**Ph**enomenon-**I**nput-o**R**gan-**E**ffect) are used for developing the model. Empirical evaluation confirms that designing can be modeled with the activity and outcome elements. The paper concludes with the identification of areas that require support and future work.

Keywords: framework, activity, outcome, conceptual design, physical law, physical effect, model

1 Introduction

Design is a process spanning from the identification of a need to a point where a solution for the need is detailed to a level such that the perceived need can be satisfied. Ever since the inception of design research, researchers have been in pursuit of studying design to better understand the phenomenon of designing. One such effort in [1] infers that: "Design is a complex activity, involving the interaction between artifacts, people, tools, processes, organizations and environment in which design takes place." The complex nature is attributed to design because of the large number of factors within each such element and simultaneous interaction between these factors.

'Complexity' in design has been the prime mover for design researchers and there have been efforts in all directions to alleviate the associated complexity. One such effort is by developing a framework of design to help in better understanding of design and designing. There have been several case-studies from design research literature where researchers have developed models and frameworks by descriptive and prescriptive methods.

A model of designing is taken here as an abstraction of the phenomenon of design that captures artifacts, tools, processes, organizations and environment. An ideal model should be able to capture all the above elements within it. However, current models, while being rich in one element or the other, fail to capture others. A framework of designing is defined here as a prescription of how designing should be carried out in order to improve its quality.

The research outlined here is to develop and evaluate a model of designing primarily to address conceptual and early embodiment design that explicitly uses: (a) Activities, and (b) Outcomes, (i.e. artifact and process elements) with emphasis on physical laws and effects, and based on the findings, propose a framework for designing.

2 Literature Survey

2.1 Importance of Conceptual Design

Conceptual design is the most creative phase of the design process. Concepts of solutions are developed during this phase to meet the requirements of the design problem [2]. Most of the changes in the product are best affected when they are worked at conceptual design stage. On average, 80% of the cost of the total life-cycle of the product is committed during this phase [3, 4]. However many difficulties are faced in conceptual design because of its open-endedness in issues of selection of components, component configurations, etc.[5]. However, relatively less effort has gone into supporting this phase of design.

2.2 Importance of Activities

Activities are viewed as the human problem solving phases in an engineering design process [6, 7]. Capturing activities in a design process is significant as they are essential for the successful development of the product [8].

There are a number of models from the literature that have included activity as a major part of their model. For instance, a Generate-Evaluate-Decide model for mechanical engineering design process is proposed in [9], a Generate-Evaluate-Select model is published in [7], activities Identify, Analyse, and Choose in the problem understanding phase and Generate, Evaluate, and Select in the problem solving phase have been identified in [10]. These activity-models are descriptive, i.e. developed after analyzing protocols of designers at work. On the other hand a prescriptive Generate-Evaluate-Modify cycle for designing micro-sensors is proposed in [11].

2.3 Importance of Outcomes

Outcomes of a design refer to the properties of an artifact which can be at any level of abstraction used to specify the artifact at that level of abstraction. In [10] the advantages of capturing outcomes of a design process are revealed as they seem to influence various aspects, like requirements identification and satisfaction.

There are a number of models and frameworks from the literature that are primarily based on outcomes. For instance, the Theory of technical systems in [12] identifies four levels – process, function, organ and assembly – to describe a technical system, Domain theory in [13] identifies three domains-transformation, organ and part-for any mechanical artifact to be designed, SAPPhIRE model of causality which consists of elements – action, state change, physical phenomena, physical effects, organs and parts - for explaining the behavior of natural and engineered systems is proposed in [14]..

2.3.1 Importance of Physical Laws and Effects

Many researchers have advocated the importance of designing with physical laws and effects which can help produce novel and creative products [11, 15–17]. However, synthesizing artifacts directly from physical effects is hard since effects were mainly created by scientists for explanation of phenomena rather than for synthesizing artifacts that embody these phenomena and synthesis using them requires more than a straightforward application [17, 18].

Even though many authors have talked about the advantages of using effects and laws while designing, these have not been adequately represented in the current models and frameworks of designing.

2.4 Importance of shared understanding

Several researchers use different terms to mean similar things and often used the same term to mean different things. [10] reports that the use of different terms to describe the design process makes it difficult to compare various descriptive findings. [19] has also pointed out a lack of shared understanding of the design activities that are performed in a design process. In [19, 20] efforts have been pursued to address commonness.

2.5 Motivation

From the above sections (2.1-2.4) the authors perceive a need for a more comprehensive design framework that should be able to integrate activity elements with outcome elements, while being able to use this framework to explain and predict the typical traits of designs and designing. Current design models and frameworks lack in comprehensiveness: while being able to represent or explain certain aspects of design, they lack in others. [10] specifically stresses the need for an in-depth understanding of the design process in terms of activities and outcomes. Apart from being comprehensive in representing the elements of the design process, a framework should help alleviate from problems and doubts of subjectivity.

3 Research Methodology

The research methodology for carrying out the objectives is outlined below.

3.1 Development of a Model

The model is developed by integrating the activity- and outcome-based elements of designing. Various models from the literature are investigated to identify the required features.

3.2 Empirical Evaluation

To check whether the developed model is a part of a natural way of designing, it was validated against protocol studies of design sessions. The design sessions in a video format were used from an earlier study [21]. The video sessions were transcribed into written data and were coded (refer Sections A.1 & A.2) following the usual guidelines from [22]. The design sessions were on observational studies of teams, T1 and T2 of three designers each who solved design problems, P1 and P2, using three different methods, M1, M2, and M3[1], as per Table 1 under laboratory conditions. Both the design problems, P1 and P2, dealt with developing conceptual-level solutions and 30 minutes was allotted for each of them. The designers were instructed to have a loud discussion and also record important findings. The design-sessions of the two teams were assisted by a researcher each to help clarify any queries the team had while solving the problem. All the problems were solved back-to-back and discussion across the teams was not allowed. Even though the same team solved the same problem twice using different methods, it need not be construed as a drawback because the authors here are interested in the degree of generality in the pattern of problem solving across a variety of design sessions.

The protocols are analyzed to identify and explain not only the two elements of designing of focus: activities and outcomes, but also the various typical composite stages such as synthesis, analysis etc. A two-way mapping was used for the protocol studies: (i) To check if all instances in the protocol could be represented using the model elements, and (ii) To check if all the elements in the model have instances in the protocol.

[1] The authors deliberately used protocols involving methods in solving design problems because design problems are rarely solved without the help of a method, and a generic design model should be able to provide a basis both for designing with and without methods.

Table 1: Pattern of problem-solving

	T1	T2
M1	P1	P2
M2	P2	P1
M3	P1	P2

3.3 Proposal of a Framework

A framework with the activity and outcome elements is proposed to suggest how designing should be carried out.

4 Results & Discussion

4.1 Development of a Model

The model is developed by integrating the activity- and outcome-based elements of designing. Various models from literature are investigated to identify the activity- and outcome-elements for designing.

4.1.1 Activity-Model

In [9] a Generate-Evaluate-Decide model is proposed as a model of a mechanical engineering design process. Protocol studies on five individual designers was used and ten different activities were grouped under three categories - generate, evaluate, and decide, to describe the design process. The protocol data was classified into the above activities, portions of the classified data were selected at random, and analyzed to recognize patterns of design activity. Most of the patterns are described by four types of sequence: generate and test, generate and improve, means end analysis and deductive thinking. These patterns constitute generate, evaluate and decide activities, in general. However, these studies focused on only portions of the design process instead of focusing on design as it continuously progressed.

In [7] descriptive studies were used to propose a component-based prescriptive model-PROSUS (Process-based support system)-which primarily consists of (a) Activities (Generate, Evaluate, and Select) and (b) Issues (problem statement, requirements, function structure, concept design, detail design, manufacturing etc.). Generate, Evaluate, and Select was proposed at each of the levels-problem statements, requirements, function structure, concept design, detail design, manufacturing etc.

In [10] a model of the design process was developed which divides the design process into two phases: problem understanding and problem solving. Three primary-level activities were identified for each of these phases namely, identify, analyse and choose for problem understanding, and generate, evaluate, and select for problem solving. In line with the definitions in [10] identify, analyse and choose seem similar to generate, evaluate, and select. Several secondary-level activities were identified under each of the primary-activities for each of the phases.

In [11] a theoretical model for the design of micro-sensors is developed, where design concepts are generated, behavioral problems of the concept are identified and the problems are fixed. This cycle seems analogous to generating design concepts, evaluating the concepts to identify behavioral problems (if any) and modifying the design to fix up the identified problems. However, these findings are not supported by any empirical data.

From the above case-studies it could be inferred that activities-generate, evaluate, modify and select-maybe involved in a design process. A GEMS (generate-evaluate-modify-select) model is proposed as a model of activity.

4.1.2 Outcome-Model

Even though there are many models in the literature that use ‘outcomes’ in various forms and levels of abstraction, the authors were only interested in a model that explicitly uses ‘physical laws and effects’ for designing, which is one of the primary aims of this paper. In spite of the importance stressed on physical laws and effects, these have not been adequately represented in the current design models. The authors found the SAPPhIRE model of causality [14] (see Fig. (1)) to be using effects and laws explicitly. Apart from laws and effects the model uses other elements-action, state change, parts, phenomenon, input, organ- to provide a much richer description of an artifact. However, the model was developed originally to explain the causality of natural and engineered systems and has not been tested for its ability to design.

The above facts motivate the authors to use the SAPPhIRE model as a model of outcome.

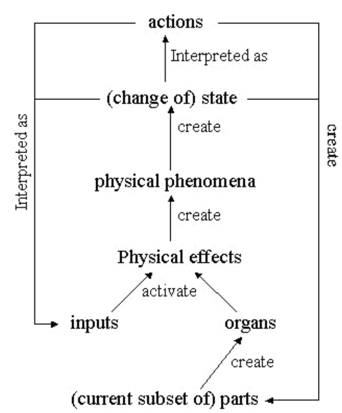

Fig 1: SAPPhIRE model of causality [14]

4.2 Empirical Validation

4.2.1 Activity Findings

The protocol studies confirmed the presence of activities: generation, evaluation, selection, and modification in the design sessions (see definitions in Appendix A.1).

4.2.1.1 Individual Activity Findings

Table 2 shows the way the activities have been identified in the protocol with an example for each activity from the protocol. Fig. (2)-(7) show the percentage frequency distribution of the individual activities in each of the six protocols.

The following results and discussions are inferred from Fig. (2)-(7):

(i) It is clear that the instances of activities in all cases in descending order are: generation, evaluation, selection and modification, irrespective of any design method, problem or team. It would be logical to argue that the design outcomes are generated first but only some of them are evaluated (see Section 4.2.1.2 on Activity Patterns).
(ii) The percentage of selection and modification approximately sum together to equal the percentage of evaluation. Therefore, it could be inferred that evaluated outcomes are either selected or modified.
(iii) The percentage of modification was observed to be less when compared to selection in all the cases. It could be for twofold reasons: firstly, all the design sessions were timed for 30 minutes only and that designers wanted to accept (and hence, select) rather than modify and secondly, design exercise required the designers to come up with an original design rather than re-design.
(iv) One could argue that if selection was identified then rejection would also be a part of the design process. However, the authors could not find instances of explicit rejection because of short time durations (by designer standards) that designers could not afford to reject outcomes and maybe preferred to modify them.

This section concludes with the fact that the instances from the protocol could be represented using activities – generate, evaluate, select and modify.

Table 2: Instances of individual activities from protocol

Activity	Protocol Instance
G	D1: So, what has to be achieved is that the campus has to kept free from dry leaves *(Generation: Campus to be kept free from dry leaves)* *[Episode: Designer defines the purpose of design exercise by generating a requirement]*
E	D1: Second is sweeping D1: Is sweeping okay? *(Evaluation: Checking the worth of sweeping)* *[Episode: Designer generates an idea for clearing-off dry leaves and estimates its worthiness]*
M	D1: Instead of manual sweeping, collections is a better term *(Modification: Change from 'manual sweeping' to 'collection')* *[Episode: designer generates a solution for clearing dry leaves (manual sweeping) and then feels collection maybe a more general term]*
S	*D1:* Some secret code is required because each individual will have it differently D2: Yeah *(Selection: D2 accepting the solution proposed by D1)* *[Episode: First designer generates a solution to have a safe, private locking system which is accepted by the second designer]*

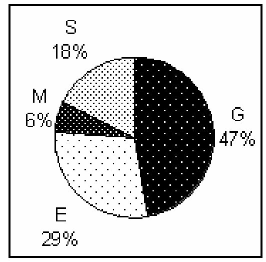

Fig 2: P1 by T1 using M1

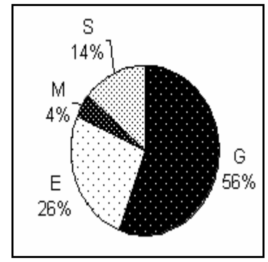

Fig 3: P2 by T2 using M1

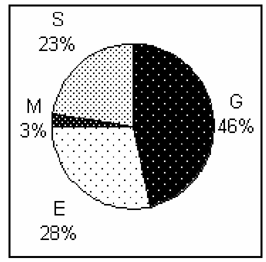

Fig 4: P2 by T1 using M2

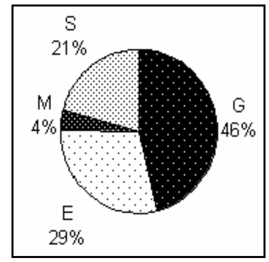

Fig 5: P1 by T2 using M1

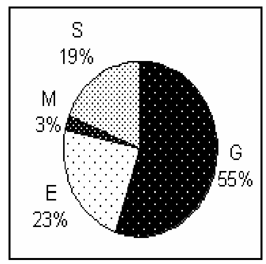

Fig 6: P1 by T1 using M3

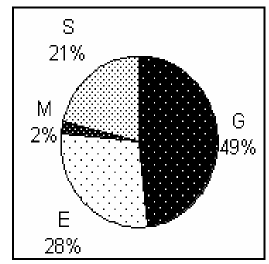

Fig 7: P2 by T2 using M3

4.2.1.2 Activity Patterns Findings

Table 3 shows examples of the prominent activity patterns from the protocol. Fig. (8)-(13) show the percentage frequency distribution of the different activity-patterns observed for each of the six cases.

The following inferences can be drawn from Fig. (8)-(13):

(i) Based on the pie charts, the prominent patterns of activities in descending order are: G, GES, GE and GEM, across all design methods, problems and teams.
(ii) It would be logical to conclude that activity patterns should culminate in selection. However, the authors observe many activity patterns to end in either evaluation or modification. This could be because these outcomes are either not considered, or implicitly evaluated and selected. Some patterns have generation only and the associated outcome has not been considered later.
(iii) Certain patterns have multiple evaluations, selections and modifications. This could be because the designers are working in a team and each member could have his/her own point of view leading to different criteria for evaluation followed by selection or modification. It could also point to the iterative nature of design.
(iv) In an episode (defined in Appendix A.1), activity patterns generally follow a sequence of generation followed by evaluation leading to modification or

selection. Depending on the acceptance or rejection of the outcome, there might be more evaluations leading to selection or modification as seen in Fig. 14.

Table 3. Instances of common patterns from the protocol

Activity Pattern	Instance from protocol
G	D1: system's primary useful function-it should lock when it is required to lock and open when it is required to open *(Generate: function of lock)* *[Episode: A designer states the purpose of a locking system, before designing it]*
GE	D1: Why don't we have an implanted, body-planted chip? *(Generate: implantation of body-planted chip & Evaluate: worthiness of implanted body-planted ship)* *[Episode: A designer generates an idea for a key to a locking system, which the user can carry anywhere, without having to remember/forget that he/she has the key]*
GES	D1: Concept is to sense something from the physical body and then process it, and operate D2: (thinks)Yeah *(Generate: sense something from physical body and process; Evaluate(implicitly-D2's thought process):(worthiness of) sense something from physical body and process; Select: sense something from physical body and process)* *[Episode: Designer 1 generates an idea for sensing something from one's body, to operate locking system and designer 2 supports)*
GEM	D1:Those (existing locking systems) structures have components, it has got levers D2: (thinks) It has got plungers actually *(Evaluate and Modify)* *(Generate: levers in existing locking systems; Evaluate: locking systems (to check whether they have levers or anything else; Modify: levers→plungers)* *[Episode: Designers analyze the structure of the locking system]*

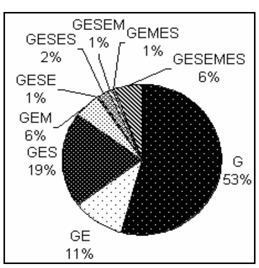

Fig 8: P1 by T1 using M1

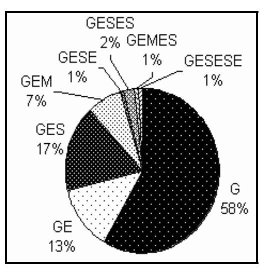

Fig 9: P2 by T2 using M1

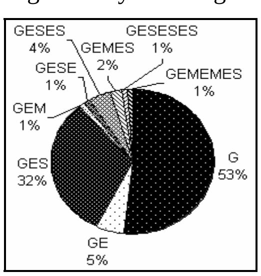

Fig 10: P2 by T1 using M2

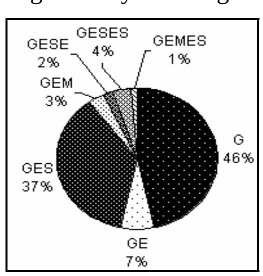

Fig 11: P2 by T2 using M2

4.2.2 Outcome Findings

This section reports findings and discussions of outcomes. The protocol analysis confirmed that design can be modeled using the elements of SAPPhIRE.

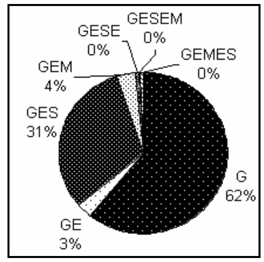

Fig 12: P1 by T1 using M3

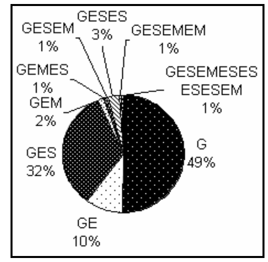

Fig 13: P2 by T2 using M3

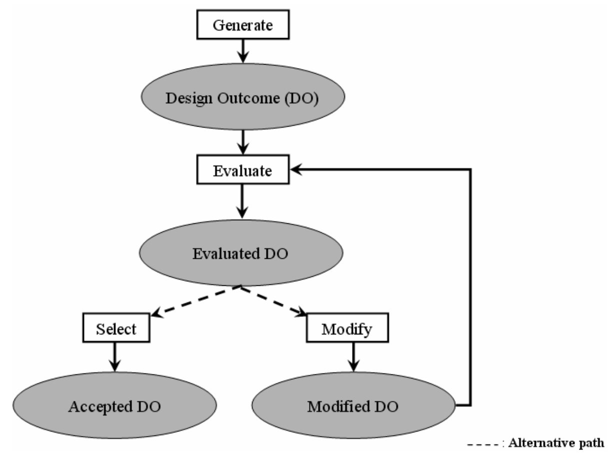

Figure 14: Activity-model of design

4.2.2.1 Individual Outcome Findings

Table 4 shows instances of the outcomes from the protocol. Fig (15)-(20) show the percentage frequency distribution of the outcomes for the six cases. The inferences and discussions below are drawn from the above figures:

a) A high incidence of action-level description is noticed in all the cases since these were derived or taken directly from the design problems given to designers.

b) A low percentage of state change-level description was observed because state change is another way of expressing action, and instances of state change could have been included under action.

c) A high-percentage of part- and phenomenon-level descriptions was identified, probably because designers in general possess good part-knowledge and understand phenomena better.

d) The percentage of effect- and organ-level descriptions was low. It could have been due to one or more of the following reasons: (i) effects and laws are not a part of natural way of designing, (ii) designers lacked effects/laws knowledge, (iii) designers did not know how to use them, (iv) problems did not require use of effects, or (v) methods did not specify use of effects.

Similar results were also reported in a different study in [23].

4.2.2.2 Outcome Patterns findings

Table 5 shows the various line-diagrams depicting the patterns of outcomes observed from the protocol studies.

The diagrams in the table show the relationship between the elements of the Sapphire model as observed.

The findings and discussions from the table are as follows:

a) In all the cases the designers started solving the problem from an action-level description.

The diagrams feature descriptions of higher-level abstractions to lower-level abstractions i.e., starting from action-level descriptions and ending up with part-level descriptions passing through one or more of the intermediate-levels of abstraction like phenomenon, state change etc. In most cases there is a direct jump from action- or phenomenon-level to part-level description. The transition from a higher-level abstraction to a lower-level abstraction confirms the *synthetic nature* of design.

b) Contrary to (b), action-level and phenomena-level descriptions were also derived from phenomena-level and part-level descriptions respectively. This fact again seems to confirm the strong part knowledge of the designers as they knew the working and the function of the part. This transition from a lower-level abstraction to a higher-level abstraction confirms the *analytical nature* of design.

c) In all the cases, design sessions culminated with a part-level description but not detailed to the extent of manufacturing. This is expected for a conceptual design problem.

Table 4: Instances of SAPPhIRE from protocol study

SAPPhIRE constructs	Instances
a (i)	D1:So, what has to be achieved is that the campus has to be kept free from dry leaves *(Action: Interpreted as dry leaves → no dry leaves)* *[Episode: Designer states the requirement to be fulfilled i.e., keep the campus free from dry leaves and at a higher level of abstraction, closer to the problem]*
s	D1:System's primary useful function is that it should lock when it is required to lock and open when it is required to open *(State change: unlock → lock or lock → unlock)* *[Episode: Designer stating the purpose of the lock, which has to be designed and is closer to a solution]*
p	D1: transportation can be done by carrying the bins and baskets manually, small trucks or tractors *(Part: Bins, baskets, small trucks, tractors)* *[Episode: Designer generates ideas for transporting dry leaves from one place to another]*
ph	D1: So, the functions that the system will take care of are: cleaning, loading, transportation, unloading and disposal of dry leaves. *(Ph: cleaning, loading, transportation, unloading and disposal)* *[Episode: Designer generates the process of keeping the campus free from dry leaves]*
r	D1: So input is gravity, self-weight, weak link *(Organ: Weak link)* *[Episode: designers reasoning the factors responsible for the fall of a leaf]*
e	D1: Because, of the force of gravity-gravitational force (D2 writes on the paper) *(Effect: Newton's law of gravitational force)* *[Episode: Designer explains the cause of fall of a leaf]*

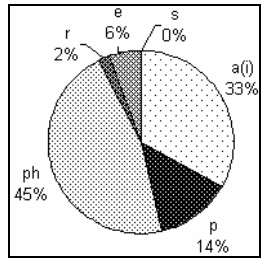

Fig 15: P1 by T1 using M1

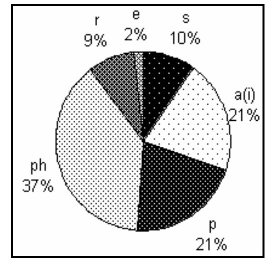

Fig 16: P2 by T2 using M1

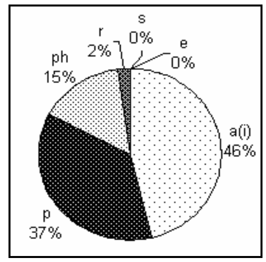

Fig 17: P2 by T1 using M2

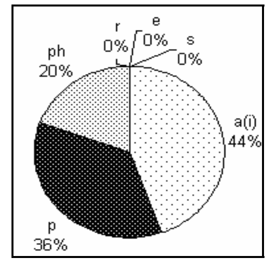

Fig 18: P1 by T2 using M2

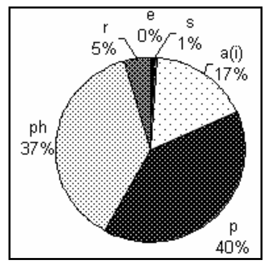

Fig 19: P1 by T1 using M3

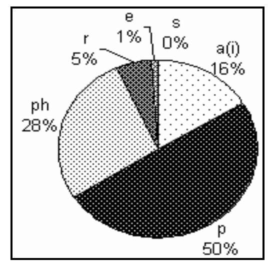

Fig 20: P2 by T2 using M3

4.2.3 Combined - Activity and Outcome Findings

Table 6 & 7 report the combined activity and outcome findings from all the six sessions. The inferences and the discussions that follow can be inferred from the tables:

(a) Action, part and phenomenon had several instances of generation, evaluation, selection and modification. These outcomes also had activity-patterns involving multiple evaluation, selection and modification.

(b) On the contrary organ and effects had very few instances of individual activities. No modification was observed for effects. These outcomes did not have activity patterns involving multiple evaluation, selection and modification. These findings could again point to the difficulty that designers face when working with effects and organs.

(c) Even state change did not have any modifications and activity patterns involving multiple evaluation, selection and modification. It could be because some state change-level descriptions could have been included under action because of little differences between the two outcomes.

This section concludes with a model that has GEMS at action-, phenomenon-, organ- and part-level descriptions and a GES-model at effect- and state change-level descriptions.

Table 5: Patterns of outcomes

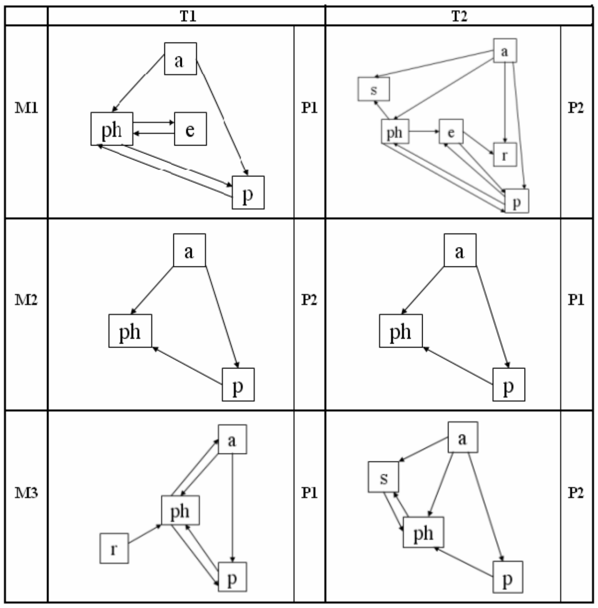

Table 6: Frequency of activities for different outcomes

Activity	a(i)	p	ph	r	e	s
G	244	308	311	38	15	15
E	125	174	179	12	6	3
M	16	17	27	4	0	0
S	86	131	119	6	5	3

Table 7: Frequency of activity patterns for different outcomes

Activity-patterns	a(i)	p	ph	r	e	s
G	130	158	168	26	10	12
GE	23	22	30	2	0	0
GES	70	102	79	6	4	3
GEM	12	8	11	4	0	0
GESE	0	3	2	0	1	0
GEMES	1	5	1	0	0	0
GESES	5	6	5	0	0	0
GESEM	1	2	2	0	0	0
GESESE	0	1	1	0	0	0
GEMEMES	1	0	0	0	0	0
GESESES	1	0	0	0	0	0
GESEMEM	0	0	1	0	0	0
GESEMES	0	0	11	0	0	0
GESEMESESESESEM	0	1	0	0	0	0

4.3 Proposal of a Framework

The empirical results reveal that very less effects and organs are used when a higher number is expected. Also, not all activities are found at all the outcome-levels pointing out to the difference in degrees of application of the outcomes. Since novelty is a critical issue in any design, one has to encourage the use of laws and effects in designing. Hence, the authors propose a framework: GEMS of SAPPhIRE, by suggesting GEMS to be carried out at all the levels of SAPPhIRE. However, the framework still needs to be evaluated (made explicit by the 'question mark' in the title) to check if novel designs can indeed be constructed.

5 Conclusions

The following conclusions can be drawn from this paper:

(a) A model that integrates the activity- and outcome-based elements has been developed and validated.

(b) Natural way of designing can be modeled with (i) activity-elements (ii) outcome-elements.

(c) There is a need to support designers with knowledge of physical laws and effects to encourage designing novel products.

(d) The uniqueness of the framework as a support for 'Design for Novelty' still needs to be evaluated.

(e) The framework is currently limited to supporting only conceptual and early-embodiment design and needs to be extended to support the other phases of design which is planned for future research.

(f) The authors intended a framework for sensors but literature survey pointed to issues for a generic technical system. However, the framework still needs to be evaluated with sensor design problems.

References

[1] L.T.M. Blessing, A. Chakrabarti, K.M. Wallace, "A Design Research Methodology," *Proc of the International Conference on Engineering Design (ICED), Prague*, 22-24 August 1995, pp 50-55.

[2] G. Pahl and W. Beitz, Engineering Design: A Systematic Approach, Spriger-Verlag, London ,UK, 1996.

[3] R. Regno, "Side-effects Detection in Sensors," Masters' Thesis, EDC, Cambridge, UK, Sep 2000.

[4] A. Chakrabarti, P. Langdon, Y.C. Liu and T. P. Bligh, "An Approach to Compositional Synthesis of Mechanical design Concepts Using Computers," Cha. 11, Engineering Design Synthesis-Understanding, Approaches and Tools, Ed by A. Chakrabarti, Springer-Verlag 2002, pp. 179-197.

[5] M. Campbell, J. Cagan, and K. Kotovsky, "Agent-Based Synthesis of Electro-Mechanical Design Configurations," Proceedings of DETC98, ASME Engineering Technical Conference, Atlanta, GA, USA, Sep 13-16, 1998.

[6] H. Simon, The Sciences of the Artificial, MIT Press, Massachusetts, USA, 1989.

[7] L.T.M Blessing, "A Process-Based Approach to Computer-Supported Engineering Design," PhD Thesis, University of Twente, The Netherlands, 1994.

[8] Cooper R G, New Products: What Distinguishes the Winners?, Research Technology Management, November-December, 1991, pp. 27-31.

[9] L.A. Stauffer, and D. Ullman, "Fundamental Processes of Mechanical Designers Based on Empirical Data," Journal of Engineering Design, Vol. 2, No. 2, 1991, pp. 113 – 125.

[10] Srinivas Nidamarthi, Understanding and Supporting Requirement Satisfaction in the Design Process, Gonville and Caius College, Cambridge, November 1999.
[11] A. Chakrabarti, A. Johnson, and T. Kiriyama, "An Approach to Automated Synthesis of Solution Principles for Microsensor Designs," International Conference on Engineering Design (ICED), Tampere, Finland, Aug 19-21, 1997.
[12] V. Hubka and W.E. Eder, "Theory of Technical Systems and Engineering Design Synthesis," Engineering Design Synthesis-Understanding, Approaches and Tools, Ed by Amaresh Chakrabarti, Springer-Verlag, 2002, pp. 49-65.
[13] C. T. Hansen and M. M. Andreasen, "Two Approaches to synthesis based on the domain theory," Cha. 6, Engineering Design Synthesis-Understanding, Approaches and Tools, Ed by Amaresh Chakrabarti, Springer-Verlag, 2002, pp. 93-108.
[14] A. Chakrabarti, P. Sarkar, B. Leelavathamma, and B.S. Nataraju, "A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas, Artificial Intelligence for Engineering Design and Manufacturing (AIEDAM), Vol. 19, 2005, pp. 113-132.
[15] T. Koyama, T. Taura, and T. Kawaguchi, "Research on Natural Law Database," Joint Conference on Knowledge Based Software Engineering, 1996.
[16] R. Zavbi and J. Duhovnik, "Prescriptive Model with Explicit Use of Physical Laws," Proc. of International Conference on Engineering Design (ICED), Tampere, 1997, pp. 37-44.
[17] S. Murakoshi and T. Taura, "Research on the Systematization of Natural Laws for Design Support," Proc of the 3rd IFIP Workshop on Knowledge Intensive CAD, Tokyo, Japan, December 1998, pp.141-160.
[18] A. Chakrabarti and T. Taura, "Computational Support of Synthesis and Analysis of Behaviour of Artefacts Using Physical Effects: Some Challenges," International Design Conference - Design 2006, Dubrovnik, Croatia, May, 2006.
[19] S. K. Sim and A. H. B. Duffy, "Towards an Ontology of Generic Design Activities," Research in Engineering Design, Vol 14, 2003, pp 200-223.
[20] A. Chakrabarti, T. N. S. Murdoch and K. Wallace, "Towards a Glossary of Engineering Design Terms," Proc of International Conference on Engineering Design (ICED), Praha, Czech Republic, 1995, pp. 185 – 186.
[21] A. Chakrabarti, "Towards a Measure for Assessing Creative Influences of a Creativity Technique," International Conference on Engineering Design (ICED), Stockholm, 19-21 August, 2003.
[22] T. Purcell, J. Gero, H. Edwards and T. McNeill, "The Data in Design Protocols: The Issue of Data Coding, Data Analysis in the Development of Models of the Design Process," Analysing Design Activity, Edited by Nigel Cross, Henri Cristiaans, Koes Dorst, Delft University of Technology, The Netherlands, John Wiley & Sons, 1996.
[23] P. Sarkar and A. Chakrabarti, "Understanding Search in Design," International Conference on Engineering Design (ICED), Paris, France, 2007.

Appendix

A Definitions & Coding

A.1 Definition & Coding of Activities

Table 9 shows the definition and coding of the activity elements. The activities have been defined wrt an episode which has also been defined below.
Episode: The situation within which something exists or happens, and that can help explain it.

Table 9: Definition and code of activity elements

Activity	Definition	Code
Generation	An activity which brings a design outcome into an episode. Every generation activity marks the commencement of a new episode.	G
Evaluation	An activity which judges the quality, importance, or value of an outcome in that episode.	E
Modification	An activity which brings about a change in the design outcome in the same episode.	M
Selection	An activity which chooses the design outcome in that episode.	S

A.2 Definition & Coding of SAPPhIRE Elements

Table 10 shows the definitions which were adopted from [14] and codes used for protocol. While coding outcomes, input-output description was included under action and so, separate instances of input are not found.

Table 10: Definition and codes of SAPPhIRE elements

Element	Definition	Code
Action	An abstract description or high level interpretation of a change of state, a changed state, or creation of an input.	a(i)
State (change)	The attributes and values of attributes that define the properties of a given system at a given instant of time during its operation.	s
Input	The energy, information or material requirements for a physical effect to be activated; interpretation of energy/material parameters of a change of state in the context of an organ.	-
Physical phenomenon	A set of potential changes associated with a given physical effect for a given organ and inputs	ph
Physical effect	The laws of nature governing change.	e
Organ	The structural context necessary for a physical effect to be activated.	r
Parts	A set of physical components and interfaces constituting the system and its environment of interaction.	p