Design mechanism and constraint diagram[1]

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Short Title: "Design diagram"

Abstract

This paper describes a model of design, called a design mechanism and constraint diagram. The model used integration definition (IDEF) notation to provide explicit treatment of mechanisms for, and constraints on, design activities. The model was able to accommodate design related activities from the enterprise level through to activities of individuals (e.g. decision making processes). With a proposed generic design activity (GDA), the model provides a means of positioning diverse design methods relative to each other. Areas which may benefit from additional design research were identified as: (1) The need to help the designer anticipate constraints from incomplete information, and negotiate for the selective relaxation of constraints in over-constrained design spaces. (2) The need to accommodate multiple viewpoints, cope with uncertainty of analysis (incompleteness of knowledge), propagate uncertain variables, and accommodate varying degrees of information

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abstraction. (3) The lack of robust mechanisms for recording and retrieving the design intent.

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1 Introduction

Design is a complex creative activity. Three of the areas of complexity are the existence of different domains (e.g. product design, machine design, etc.), different individual approaches in the level of structured process used, and different design activities depending on the time stage (e.g. concept design, detailed design, etc.). This situation is illustrated conceptually in Figure 1, with the above attributes modelled as independent dimensions. The figure illustrates the design space typically occupied by one type of designer. Others may operate in a different part of the space, possibly without overlap, and yet still be considered designers. Consequently, there are many definitions, models, methodologies, and personal preferences for design.

To set the context for 'design' in this paper, the authors adopt the definition of Hubka and Eder (1996) who wrote:

> ‘*The task of designing consists of thinking ahead and describing a structure, which appears as (potential) carrier of the desired characteristics (properties, particularly the functions). One can express this statement also in process terms: designing is defined as the transformation of information from the condition of needs, demands, requirements and constraints (including the demanded functions) into the description of a structure which is capable of*

fulfilling these demands. The demands must include the wishes of the customers, but also all stages and requirements of the life cycle and all intermediate states that the product must pass through' (p4).

Many other definitions are possible, some of which are listed by Hubka and Eder (1996), but the above definition was selected as it includes the concept of physical structure being a carrier for function, it acknowledges the origins of the demands (including those of the customer), it pays more attention to constraints than many other definitions of design, and it incorporates the life cycle considerations (viz different viewpoints).

There have been many prior models of the design process, including the simple linear model (Finger and Dixon, 1989 a, b) (BS7000, 1989), functional modelling (Pahl & Beitz, 1988), design science (Hubka, 1987; Hubka & Eder, 1996), total design (Pugh, 1991) and derivatives (e.g. Raine, 1998), business environment (Hales, 1994), network (Crisp, 1986), designer's process (Candy et al, 1996), communications (Wallace, 1987), phase diagrams (Hales, 1994), project management, design structure matrix (Yassine et al, 1999; Yassine and Falkenburg, 1999), and signposting (Clarkson and Hamilton, 2000), among others. Each model takes a particular perspective of the design process, illustrating the perceived ideal design process, or serving as a repository for knowledge about that perspective, or including a methodology by which that perspective can practically be applied to the design process. Some of the models, e.g. Candy et al (1996), are conceptual rather than detailed, and consequently do not provide specific processes. Other models are are systematic, e.g. Hubka & Eder (1996), but can suffer from being intimidating and difficult to engage with (Eder, 1998; Frost, 1999). The residual problem is that the existing models find it difficult to encompass the full scope of design complexity (as per Figure 1). The existing models of design typically use flowcharts to represent the conceptual stages or activities involved with design, focussing on diagramming the inputs and the outputs of the process. The models usually show that the design stages influence each other, but seldom explicitly identify the nature of the influence or the constraints. Nor are the diverse methodologies and tools (mechanisms) that support the design process made explicit. Consequently, the models tend to be focussed on particular domains, stages, or methodologies. Thus, it can be difficult to integrate the models with each other.

The hypothesis of this paper was that a descriptive meta-model could be developed, representing the epistemology of the methods for performing design in technical systems. The model should accommodate (1) multiple dimensions of design complexity (domain, approach, time stage), (2) all design related activities from the enterprise level through to activities of individuals (especially decision making processes), and (3) provide a holistic treatment of existing design methods, especially to position them relative to each other, and identify areas weak in supportive methodologies. This is worth doing because of the potential support it could give to the design process. Products are required to have a high degree of optimisation of function, risk and cost. Consequently, design is increasingly complex and requires multi-disciplinary and concurrent processes. Any support of the design process that can be obtained from a better understanding of design, and better accessibility to design methodologies, is advantageous.

2 Development of the model

A model of design needs to include the following features:

- design activities, (e.g. verb-noun description)
- resources that are consumed in the activity
- deliverable outputs produced by the activity
- methodologies and tools (mechanisms) that support the design process
- constraints within which the designer must operate
- different levels of detail, from macroscopic to microscopic.

A method of analysis was developed to provide these features, and then applied to analyse the epistemology of design (Pons, 2001) . The method was to use a structured, deductive process to decompose the design process into multiple sub-processes. For each of these it was then necessary to determine the initiating events, controls, inputs, supporting mechanisms (e.g. design tools), and the outputs. This process was repeated as necessary to provide additional detail. Descriptive and explicit consistency was enforced between objects (arrows) and associated activities (blocks). This enforces a rigour that can be lacking in other flowchart approaches. The developing model was inductively reconciled with existing knowledge about design. This involved successive refinement, even redefinition, of the model to plausibly incorporate the observations of others.

The resulting model was expressed as a series of flowcharts using the integration definition zero (IDEF0) notation (FIPS, 1993, Addy and Simms, 1996). This was selected as it is very much better than other flowcharts at depicting complex processes such as design. The block in an IDEF diagram represents an action. The inputs (if any) are transformed or even consumed by the function in the block, to produce one or more outputs. Input arrows are always on the left of the block, and outputs on the right. Controls (here usually termed Constraints) enter above the block and initiate or ensure the output is correct. The mechanisms (if any) that support the function enter under the block. The IDEF notation therefore permits inputs and outputs to be clearly distinguished from other factors that influence the activities, so the diagrams contain more information than the plain flow diagrams of other design models. Also, IDEF readily permits multiple levels of model. The IDEF notation was likewise used by Court et al (1996) to explore a related but different aspect, namely how designers access information.

With other flowchart notations the meanings of the arrows is seldom explicit, and they generally represent sequence of activities (or influence). However, with IDEF it is essential to note that arrows convey objects to activities. Therefore, an activity may begin autonomously when its required inputs are available and its constraints permit. Consequently, the IDEF notation readily provides that multiple activities can be simultaneously active, and thus supports the modelling of concurrent engineering processes. It also supports sequenced (serial) activities.

A key characteristic that emerged in the resulting model (Pons, 2001) was the high commonality of design mechanisms across the various dimensions of Figure 1. This suggests that design processes are more similar than dissimilar across different domains and stages. This characteristic was then represented by a 'generic design activity' (GDA). The GDA is thus a standard building block for design that encapsulates multiple design mechanisms and can be deployed in different situations. In this paper the GDA is explained down to the level of the decision making process, integrating the research of others in the process. The GDA is also developed towards the macroscopic enterprise direction.

3 Description of the design mechanism and constraint model

The model as a whole is termed the 'Design Mechanism and Constraint Model' (DMCM). In the sections below the presentation of the model starts at the enterprise level, progresses through the GDA, and ends at the level of the decision process.

3.1 Enterprise perspective of design

The enterprise level is where the macroscopic business activities occur, as shown in Figure 2. The activities are numbered and briefly described. The activity ‘Recognise need to develop new product (1)' involves a design manager or product champion initiating the activity 'Develop product (2)', in response to a management or customer stimulus. Working capital is consumed to produce a product specification. Key characteristics of the product are potentially apparent after this stage. The activity (2) is further detailed in a following diagram.

The 'Produce product (3)' activity is initiated by the upstream product specification. Production uses materials and labour within constraints. Some constraints are internal to the organisation (e.g. production capability) and others from external sources (e.g. health and safety legislation). The projected sales volume also influences the production activity. Production also generates concurrent engineering constraints for design and other activities. Additional key characteristics become evident as the final product emerges. The product is sold (4), generating sales volume and nett income.

The strategic activity to set organisational priorities (6) produces directives which prompt new product development, and allocates finance for development. Constraints here include the organisation's mission and the shareholder needs. Input finance is provided by market capital and reserves. This part of the model is not exhaustive but rather illustrative of the financial constraints that affect resource allocation (capital rationing) in product development. Project funding is thus identified in the model as an important aspect of managing design, and one over which the design manager may have limited influence.

Separately the customer measures the worth of the product (7), based on personal values and resource constraints. Implicit in here are quality management principles, e.g. identifying the voice of the customer (Gustafsson, 1996). The customer's assessment is a subjective process depending on perceptions of a number of key characteristics of the product (e.g. function). Although these key characteristics may be quantified by the manufacturer, the customer usually has only tenuous information, and the measure of product worth may be influenced primarily by perception. Likewise, the values held by the customer, and the means to satisfy them, are incompletely known to the manufacturer and form the basis for market research activities on product worth, to inform activity (1).

3.2 Model of product development

The 'Develop Product' activity is elaborated in Figure 3. The model is not prescriptive as to the work breakdown structure in a project, and the arrangement of activities in the figure is simply illustrative. It is convenient to begin the explanation at activity (1), though various activities can simultaneously be active.

Initial concepts at (1), if any, might include market pressure, bench marking against related products, and customer feedback. These are used to produce specifications for the user interface (styling) and engineering product function. Market research mechanisms include quality function deployment (QFD) (Bergman and Klefsjö, 1994) and analytical hierarchy process (AHP) (e.g. Perego and Rangone, 1996). The activity of 'Design styling (2)' is initiated by the styling specifications to produce a styling design. The activity of 'Design engineering details (3)' produces details (typically drawings) using various engineering design tools and mechanisms (e.g. computer aided design, finite element analysis). There are constraints in styling design, engineering specification, cost, material strength, corrosion resistance, reliability, and production. The next task (4) is to design the manufacturing processes, to produce tooling and specifications for manufacturing processes from the engineering drawings. The activity uses mechanisms such as computer aided design (CAD), computer aided manufacture (CAM), computer numerical control (CNC), and mould flow analysis, while operating under constraints of budget and manufacturability with existing resources and materials.

For quicker time to market it is necessary that many activities occur concurrently. The concepts of concurrent engineering will be seen to be accommodated in the model, though this is not mandatory as the model does not specify timing details.

The philosophy of this model is that design is an augmentative process, in that each design stage adds new value to the existing design, by using various mechanisms and operating under constraints. Accordingly, the output of any one design stage is not necessarily the complete creative effort, such that downstream activities were merely non-creative technician tasks. Instead the output of one design activity may be a constraint (as opposed to an input) on the next, so that further creative activities are necessary to complete the overall design. The skills of different types of designers are complementary and necessary to develop a product to completion.

3.3 The Generic Design Activity

The authors propose that all design activities, regardless of their position in the design space of Figure 1, have common sub-activities of:

- Finding a creative design solution to a problem that is partially defined by some constraints, and for which some partially developed existing concept may (or may not) exist.
- Assessing the proposed solution for suitability.
- Selecting a solution using some decision process.
- Implementing the solution to produce a detailed design.

Consequently, a generic design activity (GDA) is proposed, to be substituted in any of the design activities of Figure 3. The GDA is illustrated in Figure 4, which also locates various design tools. Conceptually, the generic design activity is a standard building block that may be deployed at various stages in the design cycle, and at as many locations as design occurs, with one or more of its mechanisms operative. Any number of generic design activities may be connected together to represent the total design cycle.

The benefits in the GDA concept are the provision of a classification scheme for design tools, and the identification of areas that may benefit from further research. It was also intended that the GDA concept provide a social benefit of reducing professional rivalry between different types of designer, by showing that design tools belong to the entire design community.

The authors propose that the internal activities of the generic design activity are:

(1) Generate candidate solution

At this stage the designer (human or artificial intelligence) takes the existing concept (if any), and uses various inventive mechanisms to create a candidate solution within prescribed constraints on how the solution should perform. These constraints could originate from upstream or downstream activities. At styling and early design the upstream inventive constraints may be provided by market survey, focus group, quality function deployment (QFD) (e.g. Martin et al, 1998), and analytical hierarchy process (AHP) (Gustafsson, 1996). If the GDA is deployed at later design stages then the preceding stages provide the constraints.

If the design is an incremental improvement on an existing design, then a well-defined input concept exists. In the more general case of innovative design there may be no existing concept and the solution must be created from scratch. The inventive mechanisms include human serendipity, brainstorming, natural analogy, systematic idea generation (Pahl and Beitz, 1988), catalogue methodologies (Kersten, 1996), theory of inventive problem solving (TIPS/TRIZ) (Zlotin and Zusman, 1999), morphological analysis (Hague et al, 1996), genetic algorithms (Schmidt and Cagan, 1993), grammars (Andersson, 1994), expert systems (Cunningham and Smart, 1993), neural networks (Noguchi, 1998).

The output is a candidate solution. It is possible that several solutions may be considered simultaneously and be in various positions within the design activity, and several design activities in a larger system may all be active. Therefore, the GDA should not be interpreted as a set of discrete state transitions but as a system of multiple simultaneously active threads.

(2) Assess Solution

The candidate solution is next assessed for validity. Mechanisms include focus groups (especially at early styling design), system simulation (throughout engineering design), functional modelling (Hubka and Eder, 1988, Oh and Sharpe, 1996), bond graphs (Cellier, 2001), feature based modelling (Fu and De Pennington, 1994), risk assessment (including qualitative, hazard and operability study, quantitative, fault tree analysis, and failure mode effects analysis, Ossenbruggen, 1994), sensitivity analysis, design of experiments, loss functions (Box et al, 1988), decision analysis & belief networks (Clemen, 1996), operational research/management science (Taylor, 1999), Fuzzy theory (Wood and Antonsson, 1989), Monte Carlo analysis (Vose, 1996) and qualitative simulation (Kuipers, 1994).

The assessment constraints may originate from prescribed upstream constraints, for example manufacturing design may receive geometric tolerances from an upstream detailed design. There are also 'reasonably anticipated constraints', which include professional judgement factors such as safety and liability. Also, the proposed solution must not violate earlier design intent, especially for incremental design or where design is reworked in response to a failure.

The primary output from this activity is a solution concept. This adds value to the original candidate solution, either by clarifying or adding new information. Additional outputs include the preliminary constraints for concurrent engineering, cf. the overlapping concept in design structure matrix (Yassine and Falkenburg, 1999). Although the design has not yet been firmed up, there may still be sufficient information for other up- and down-stream activities to begin their processes. If the candidate solution fails the assessments, then either a new solution must be generated or the design must proceed with an imperfect solution.

(3) Select solution

Here a decision is made whether or not to accept the input solution concept. Decision mechanisms include decision problem classification (Ullman and D'Ambrosio, 1995), conflict resolution, and risk/decision analysis (Clemen, 1996) (including belief networks, influence diagrams, and decision trees). The activity is constrained by concurrent engineering requirements from elsewhere in the system (up- or down-stream). However it is commonly not possible to satisfy all the constraints in a system, and a management decision might be made to give priority to one activity and require the others to compensate. The action of selecting a solution freezes part of the design and imposes constraints on other design activities.

The decision process, and the management of risk in selecting a solution may be an underdeveloped area of design research (e.g. Thornton et al, 2000).

(4) Implement solution

Here the selected solution is consolidated into a detailed design, for example by producing working drawings or models according to drawing standards. Implementing the solution creates constraints for other activities (e.g. production). If at any stage the design fails then previous activities are re-examined.

(5) Record and retrieve design intent

The activity here is to record the current design intent, and subsequently retrieve it and feed it forward as a constraint to future solution assessment. This prevents incremental design improvements from unintentionally violating a requirement that was known to earlier designers but is not self-evident in the finished artefact. Recording the rationale for a design is one part of the task, but it is essential that something initiates the retrieval process where appropriate. Design intent seems to be poorly supported by mechanisms, and the default of human memory (Court et al, 1996) is not always robust.

A separate design activity could model each designer or design team in each of the various stages of the design cycle. The GDA concept is flexible as to the composition of a team, so it does not matter how the distinctions are drawn between styling, engineering and manufacturing design.

3.4 Selecting a design solution

The discussion now turns to the 'select solution' activity of the GDA, which is explored in Figure 5. The core activity is to make a decision, which is done under management decision constraints and using various decision mechanisms (see diagram for further details). Another activity is to adjust the decision as consequences develop, e.g. the design selection of plastic rather than sheet metal for a dishwasher tub may be found to adversely affect say thermal deflection which in turn may necessitate adjustment of the design. Adjustment may be constrained by uncontrolled factors and by not knowing which factors are influential. Controllable factors ('tuning parameters', Otto and Antonsson, 1993) may be available for manipulation even once the design is complete.

Constraints on the decision making process are identified as the need to accommodate: (i) varying degrees of information abstraction, being quantitative variables (ratio and interval scales) and qualitative variables (ordinal and nominal scales), (ii) information that may be uncertain (deterministic, probabilistic or possibilistic), (iii) multiple viewpoints other than function (e.g. the capability to anticipate other views and see how a change in one area affects the system performance in another viewpoint), (iv) incompleteness of knowledge of system performance (mathematically explicit vs subjective relationships between variables). Further work by Pons (2001) was subsequently directed at developing a methodology to accommodate these four aspects during design.

Since activities such as generating a candidate solution (Activity 1, Figure 4) and making a design decision (Activity 2, Figure 5) are cognitive processes, psychological variables, especially personality dimensions and patterns of behaviour of the individual within the enterprise, will affect the design process.

3.5 Implementing a solution

Returning to the generic design activity, the implement solution activity is now explored in Figure 6. The diagram is set up for the context of mechanical product design, for which the selected solution contains information about the shape, size, function, material, and appearance.

4 Discussion

4.1 Distinguishing features of this model

The Design Mechanism and Constraint diagram is differentiated from other representations of the design process by:

(a) the explicit separation of mechanisms, controls, inputs and outputs.

(b) the ability to systematically model the macroscopic activities of the firm through to the decision processes used in design.

(c) the recursive nature of the generic design activity model, where the basic element recurs both at different stages in the product development process. This is analogous to the recursion that features in Beer's viable system model for an organisation (Beer, 1985).

The explicit separation of inputs, outputs, mechanisms and constraints in the IDEF approach was useful in ensuring completeness of the model. Without this feature there could have been a dominant focus on only inputs and outputs and an underrepresentation of constraints and mechanisms, as sometimes occurs with other flowchart methods.

The DMCD model provides a descriptive perspective that integrates many other design methodologies. It is not an inventive method as are functional modelling (Pahl & Beitz, 1988), TRIZ (Zlotin and Zusman, 1999) and others, though it shows where these methods fit in, and where they are inactive.

4.2 Validation of the model

A degree of validation is provided in the manner in which the model was constructed. During its development it was reconciled with the observations of others on design. At times this involved redefinition of the model. The model should therefore not be considered so much a hypothetical model of what design should look like, as a perspective on the current body of knowledge on design.

Incorporating problem specification

One matter that requires comment is that of problem specification. While some other methodologies mandate a formal and relatively complete problem specification before design commences (e.g. the Structured Planning approach of Owen, 1993), the GDA model is not prescriptive about this. Problem definition is implied in the GDA as prescribed inventive constraints, concurrent engineering constraints, prescribed assessment constraints, and reasonably anticipated constraints (professional judgement). Such constraints may arise from an imposed and premeditated specification, and/or from requirements that arise during the design process. The model does not explicitly provide for a degree of compulsion (Owen, 1993) against each constraint, though that is not excluded.

4.3 Identifying possible weak areas in design

The model may be interrogated to identify areas of design that are potentially weak. This is done by identifying activities with too few or too many controls or mechanisms. The problem of too few mechanisms was identified in connection with recording the design intent.

A case of too few controls appears to occur with solution creation, and this warrants a fuller discussion. The diagrams show that most of the effort that has gone into automating and supporting the design process, particularly artificial intelligence, has focussed on solution creation (as opposed to constraint generation). The position with most design tools (such as expert systems, genetic algorithms, TRIZ, qualitative simulation, and optimisation) seems to be that if there is an intractable design problem, then what is needed is a novel solution. Alternatively that design impasses are caused by a designer who is ignorant of possible solution principles. The first difficulty with this premise is that providing the required explicit specification constraints without resorting to subjective judgement is a non-trivial undertaking in many real designs. Designers may have to determine constraints from incomplete and qualitative specifications, using their professional judgement and experience. Court et al (1996) established that designers rely heavily on their memory, knowledge and experience. Second, as the above diagrams illustrate, constraints arise from multiple sources, so that over-constraint of the design space is a real possibility. To find a solution it may be necessary to relax some constraints, which involves distinguishing the degree of flexibility in multiple constraints. There are different functional perspectives (client, design, production, service, etc.) each of which may have multiple members (who may agree imperfectly with each other). Thus relaxing any constraint involves negotiation, and this subjective process is difficult to automate.

Automated design mechanisms can usually find a solution in a given domain, if supplied with complete problem and constraint definition (usually quantitative). Consequently, such automated design tools are tightly focussed on the domains for which constraints can be specified, and find the terrain difficult where constraints are qualitative or over-constrained.

Thus it appears that a primary issue in design is anticipating the constraints, that this is essential for successful solution generation, and that this may be an under-developed area of design research. Furthermore, it seems unrealistic to expect that any formal specification activity will necessarily be able to fully or even sufficiently identify quantitative constraints prior to commencement of design. Instead the constraints listed in the specification may be partly qualitative and incomplete. Consequently, expert design skills may be necessary to identify constraints suitable for design, and this process may occur concurrently with other processes. Perhaps the difficulty faced by the novice designer is not so much a lack of solution ideas as a lack of awareness of the constraints on success or how flexible given constraints may be. Anticipating the constraints is especially difficult at early design when the concept cannot be tested. The value of experience could be that it enhances the ability to anticipate both constraints and solution concepts. The TRIZ methodology suggests that there are a finite number of inventive principles, which may be combined in diverse ways. However, it is not certain that this applies also to constraints on a design. Human designers anticipate constraints on the basis of incomplete qualitative/quantitative facts and subjective knowledge, incorporating experience and professional judgement. Automated design tools are not yet able to function robustly in real design environments, and their weakness may primarily be an inability to anticipate constraints.

Too few controls/constraints as in this case suggests that the output may be variable in quality. Consequently, there may be value in developing new methods for guiding solution creation to produce consistent high-quality outcomes.

It is also clear from the model that a key activity, to select a design solution from various candidates (Figure 5), needs to be able to accommodate large uncertainties. In particular, there is a need to accommodate multiple viewpoints, cope with uncertainty of analysis (incompleteness of knowledge), propagate uncertain variables, and accommodate varying degrees of information abstraction. Existing design methodologies do not operate well with these uncertainties and in fact generally reduce the uncertainties to certain relationships, quantitative variables, and deterministic variables. Also, the mechanisms for decision making are seen to be dependent on personality and organisational behaviour factors, which the engineering design literature almost universally ignores. Design under risk, and engineering decision making under risk, are areas that need further research.

One benefit of the model is thus shown as the ability to identify possible areas for further design research. Another intended practical benefit is for designers to use it to increase their awareness of other methodologies that could be helpful in their task.

4.3 Limitations of the model and further developments

The method described here provides a descriptive and graphical model of the design process. In principle the diagrams could be successively detailed down to the level of providing detailed standardised prescriptive procedures, or even algorithms, but that is not attempted here, nor is it certain that it is feasible or desirable. The value in the model is its provision of a conceptual checklist to support rather than prescribe design processes.

A limitation is that the model is complex, since it contains much information and requires a special interpretation (IDEF). Consequently, the diagrams might be formidable to non-specialist readers. This limitation of IDEF was identified by Yassine et al (1999). They used design structure matrix methods instead to meet their objective, which was to use an algorithm to optimise dependent activities for project management.

The DMCM provides a system model into which mathematical relationships could in future be deposited and a simulation run (e.g. using Monte Carlo) to extract project schedules or other project management information. If there are qualitative variables in the model, or the relationships cannot be reduced to algorithms, then conditional probabilities could be used as a simulation mechanism.

In case it is not already apparent, it needs to be stated that a constraint (and potential limitation) of the model is its dependence on the subjective opinion of its author. It is likely that (a) no model, including this one, will ever be definitive, and (b) multiple models, from different perspectives, are possible and valid. The latter is an explicit premise of the IDEF0 modelling standard (FIPS, 1993: p14). Nonetheless, a model with limitations may still provide a useful function.

5 Conclusions

This paper has confirmed the initial hypothesis, by describing the development of a descriptive meta-model representing the epistemology of design, called a design mechanism and constraint diagram. The model accommodates multiple dimensions of design complexity (domain, approach, time stage), enterprise through to individual design activities, and positions existing design methods relative to each other.

It is suggested that design is an augmentative process whereby various mechanisms are used to add value to the design. The output of one design activity may be a constraint (as opposed to an input) on the next, so that further creative activities are necessary to complete the overall design.

Areas of design that may benefit from additional research are identified and include:

(1) The need to help the designer anticipate constraints from incomplete information, and negotiate for the selective relaxation of constraints in over-constrained design spaces. Success here would likely also enhance the

effectiveness solution generation systems, particularly the artificial intelligence tools which are dependent on explicit prior constraint formulation.

(2) The need to accommodate multiple viewpoints, cope with uncertainty of analysis (incompleteness of knowledge), propagate uncertain variables, and accommodate varying degrees of information abstraction. This area was subsequently explored by Pons (2001).

(3) The lack of robust mechanisms for recording and retrieving the design intent.

References

Addy EA, Simms LJ (1996) Experience Report: The Use of Functional Flows in IV&V. http://research.ivv.nasa.gov/~eaddy/funcflow

Andersson K (1994) Vocabulary for conceptual design. Proceedings of the IFIP TC5/WG5.2 Workshop on Formal Design Methods for CAD IFIP Transactions B: Computer Applications in Technology B18 p 157- 171

Beer S (1985) Diagnosing the system for organisations. Wiley

Bergman B, Klefsjö B (1994) Quality: from customer needs to customer satisfaction. Studentlitteratur, Sweden, ISBN 91-44-46331-6

Box G, Bisgaard S, Fung C (1988) An explanation and critique of Taguchi's contributions to quality engineering. Report No. 28, Center for Quality and Productivity Improvement, University of Wisconsin-Madison, 610 Walnut ST, Madison WI 53705 USA

BS 7000: Part 1 (1989) Design management systems. Guide to managing product design. British Standards Institution, London.

Candy L, Edmonds E, Patrick D (1996) Interactive knowledge support to conceptual design. In: SHARPE J (ed), A I system support for conceptual design. Proceedings of the 1995 Lancaster International Workshop on Engineering Design, Springer, p 260-278

Cellier FE (2001) Controllab Products - Bond graphs. Http://www.rt.el.utwente.nl/bnk/bondgraphs/bond.htm accessed on 29 May 2001.

Clarkson PJ, Hamilton JR (2000) 'Signposting': A parameter-driven task-based model of the design process. Research in Engineering Design 2000(12): 18-38

Clemen RT (1996) Making hard decisions. 2e, Duxbury Press

Court AW, Culley SJ, McMahon CA (1996), Information access diagrams: A technique for analysing the usage of design information. Journal of Engineering Design, 7(1), p 55-75

Crisp JDC (1986) Industrial Innovation and engineering education, parts I to III. Acquiring Sensivity to Innovation, Mechanical Engineering Transactions of the IEAust., p 45 - 49

Cunningham A, Smart R (1993) Computer-aided parts estimation. AI Magazine 14: 3, p 39-49

Eder WE (1998) Design modeling - A Design Science approach (and why does industry not use it?). Journal of Engineering Design, v 9 n 4 p 355-372

Finger S, Dixon J (1989a) A review of research in mechanical engineering design. Part 1: Descriptive, prescriptive, and computer-based models of design process. Research in Engineering Design, 1 p 51-67

Finger S, Dixon J (1989b) A review of research in mechanical engineering design. Part 2: Representations, analysis, and design for the life cycle. Research in Engineering Design, 1 p 121-137

FIPS (1993) Integration Definition for Function Modeling (IDEF0). Federal Information Processing Standards Publications, National Institute of Standards and Technology, http://www.itl.nist.gov/fipspubs/idef02.doc of 21 Dec 1993, last accessed 12 Aug 2003

Frost RB (1999) Why does industry ignore design science? Journal of Engineering Design, v10 n4 p297-304

Fu Z, De Pennington A (1994) Geometric reasoning based on graph grammar parsing. Journal of Mechanical Design, Transactions Of the ASME v 116 n 3 Sept p 763-769

Gustafsson A (1996) Customer focused product development by conjoint analysis and QFD. Linköping Studies in Science and Technology, Dissertation No. 418, Division of Quality Technology, Department of Mechanical Engineering, Linköping University, S-581 83 Linköping Sweden

Hague M, Taleb-bendiab A, Brandish M (1996) An adaptive machine learning system for computer supported conceptual engineering design. In: SHARPE J (ed), A I system support for conceptual design. Proceedings of the 1995 Lancaster International Workshop on Engineering Design, Springer, p 1-16

Hales C (1994) Managing Engineering Design. Longman Scientific & Technical.

Hubka V (1987) Principles of Engineering design. WDK1, Heurista, Zurich, ISBN 3-85693-018-3

Hubka V, Eder WE (1988) Theory of Technical Systems. Springer-Verlag, ISBN 3-540-17451-6

Hubka V, Eder WE (1996) Design Science. Springer-Verlag, Berlin, ISBN 3-540-19997-7.

Kersten T(1996) “MODESSA”, a computer based conceptual design support system. In: SHARPE J (ed), A I system support for conceptual design. Proceedings of the 1995 Lancaster International Workshop on Engineering Design, Springer, p 241-259

Kuipers B (1994) Qualitative reasoning. The MIT Press, Cambridge, ISBN 0-262-11190

Martin MV, Kmenta S, Ishii K (1998) QFD and the designer: lessons from 200+ houses of quality. World Innovation and Strategy Conference, Sydney, Australia

Noguchi H (1998) Exploratory study on `Cross-Inference Method' for supporting idea generation process of industrial designers. International Conference on Knowledge-Based Intelligent Electronic Systems, p 384-389

Oh V, Sharpe J (1996) Conflict management in an interdisciplinary design environment. In: SHARPE J (ed), A I system support for conceptual design. Proceedings of the 1995 Lancaster International Workshop on Engineering Design, Springer: p298-318

Ossenbruggen PJ (1994) Fundamental principles of systems analysis and decision making. John Wiley & Sons, New York, ISBN 0-471-52156-6

Otto KN, Antonsson EK (1993) Tuning parameters in engineering design. Journal of Mechanical Design, Transactions Of the ASME v 115 n 1 p 14-19

Owen CL (ed) (1993) Design for integrity. Insitute of Design Communications Center, Illinois Institute of Technology, Chicago, Illinois USA

Pahl G, Beitz W (1988) Engineering Design: A systematic approach. Springer-Verlag (Berlin) and The Design Council (London). Wallace K (ed)

Perego A, Rangone A (1996) On integrating tangible and intangible measures in AHP applications: a reference framework. Proceedings of the IEEE International Conference on Systems, Man and Cybernetics v 3 p 1836-1841

Pons DJ (2001) A methodology for system integrity in design. PhD Thesis, University of Canterbury, New Zealand

Pugh S (1991) Total Design, Integrated Methods for Successful Product Engineering. Addison Wesley.

Raine JK (1998) The design process in industry - How good are our models and management practice? Waves of Change conference, Gladstone Australia 28-30 Sept, p301-306

Raine J, Pons D, Whybrew K (2001) The design process and a methodology for system integrity. Proceedings of the Institution of Mechanical Engineers Vol 215 part B, p569-576.

Schmidt LC, Cagan J (1993) Recursive annealing: A computational model for machine design. Proceedings of the 5th International Conference on Design Theory and Methodology, American Society of Mechanical Engineers, Design Engineering Division (Publication) DE v 53 p 243-251

Taylor BW (1999) Introduction to management science. Sixth edition, Prentice Hall, New Jersey USA, ISBN 0-13-918103-2

Thornton AC, Donnely S, Erton B (2000) More than just robust design: why product development organizations still contend with variation and its impact on quality. Research in Engineering Design 2000(12): 127-143

Ullman D, D'Ambrosio B (1995) A taxonomy for classifying engineering decision problems and support systems. ASME Design Engineering Division (Publication) DE v83 n2 Pt1 p627-637

Vose D (1996) Quantitative risk analysis. Wiley, ISBN 0-471-95803-4

Wallace KM (1987) Studying the engineering design process in practice. International Congress on planning and design theory, Boston, USA 17-20 Aug, pp6

Wood KL, Antonsson EK (1989) Computations with imprecise parameters in engineering design: background and theory. Journal of Mechanisms, Transmissions, and Automation in Design v 111 n 4 p 616-625

Yassine AA, Falkenburg DR (1999) A Framework for Design Process Specifications Management. Journal of Engineering Design, vol. 10, no. 3, p 223-234

Yassine A, Falkenburg D, Chelst K (1999) Engineering Design Management: An Information Structure Approach. International Journal of Production Research, v37 n13 p 2957-2975

Zlotin B, Zusman A (1999) Managing Innovation Knowledge: The Ideation Approach to the Search, Development, and Utilization of Innovation Knowledge. http://www.ideationtriz.com/paper_Managing_Innovation.htm last updated 2 Jan 2001 and accessed on 29 Jan 2001

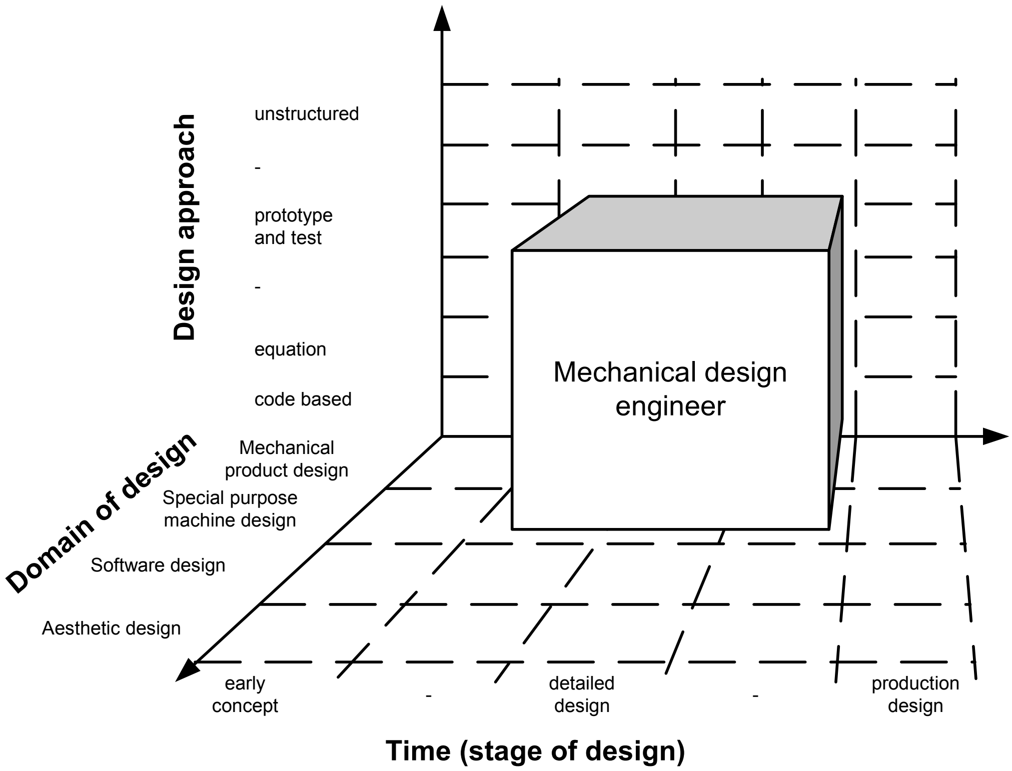

Figure 1: Conceptual model for design space, showing independent dimensions of Time, Domain, and Approach, with illustrative labels. The space occupied by one type of designer is shown, and other designers may be at a different position in the design space.

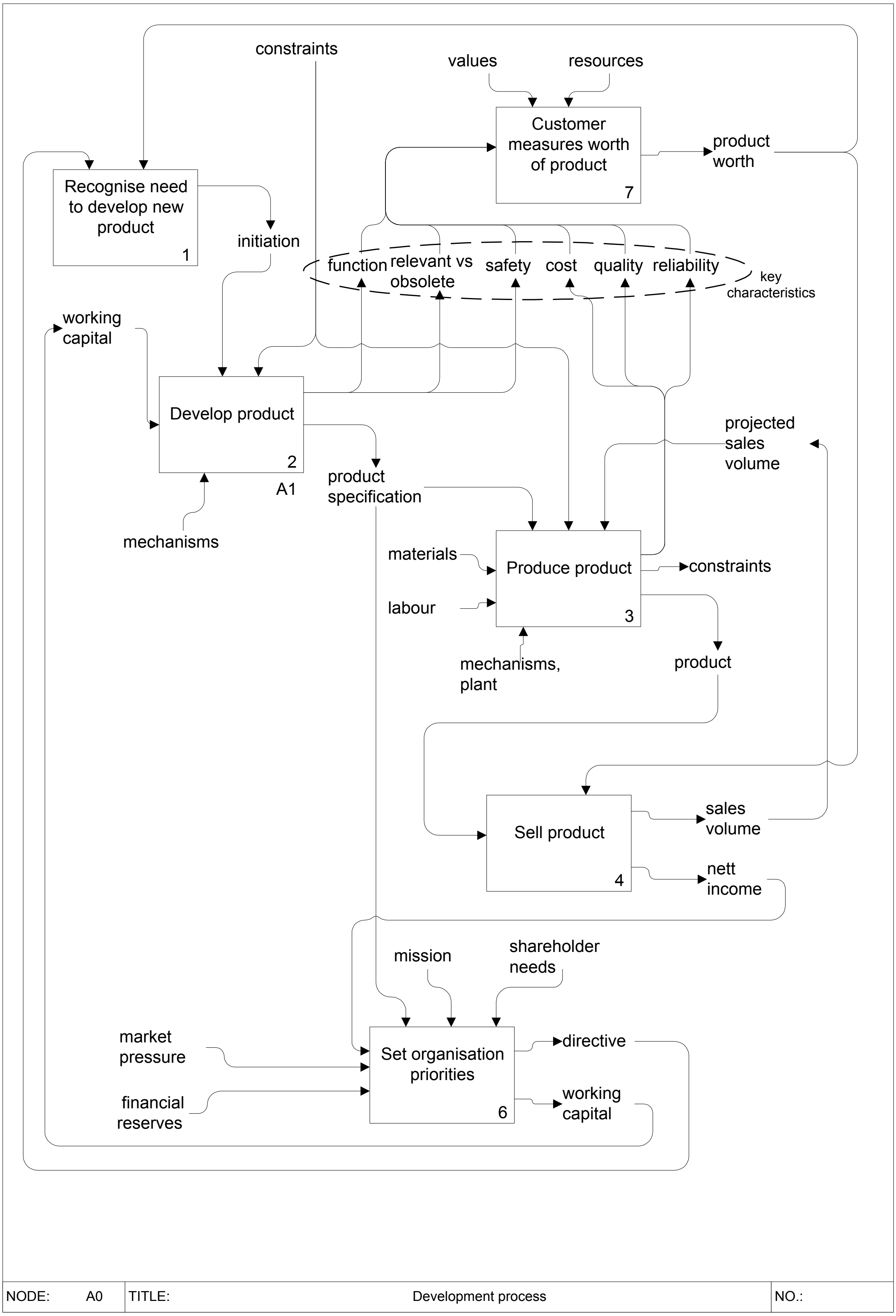

Figure 2: Design mechanism and constraint diagram at the top level.
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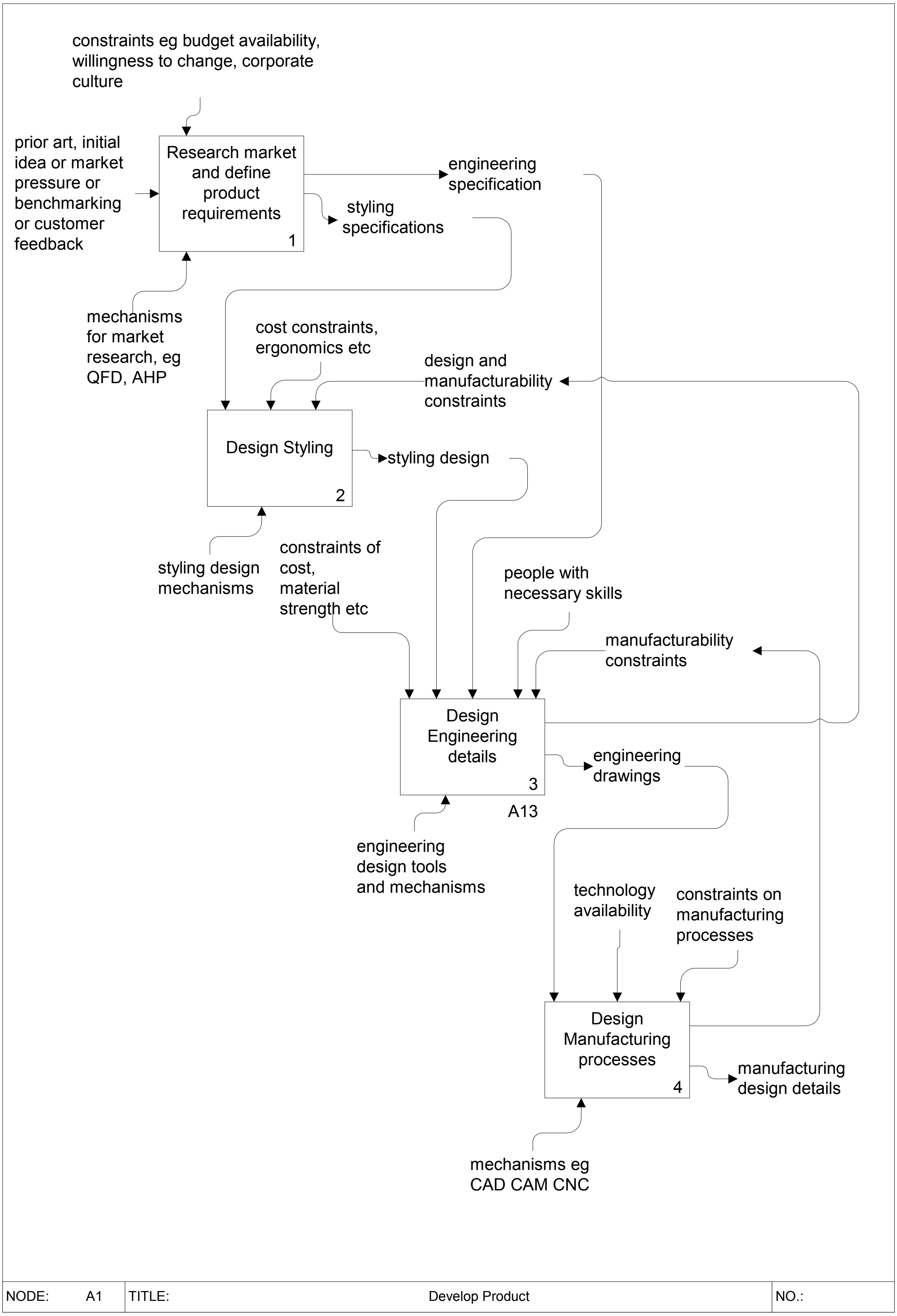


Figure 3: Design mechanism and constraint diagram for the activity of Develop product. <A1Stages.wmf>

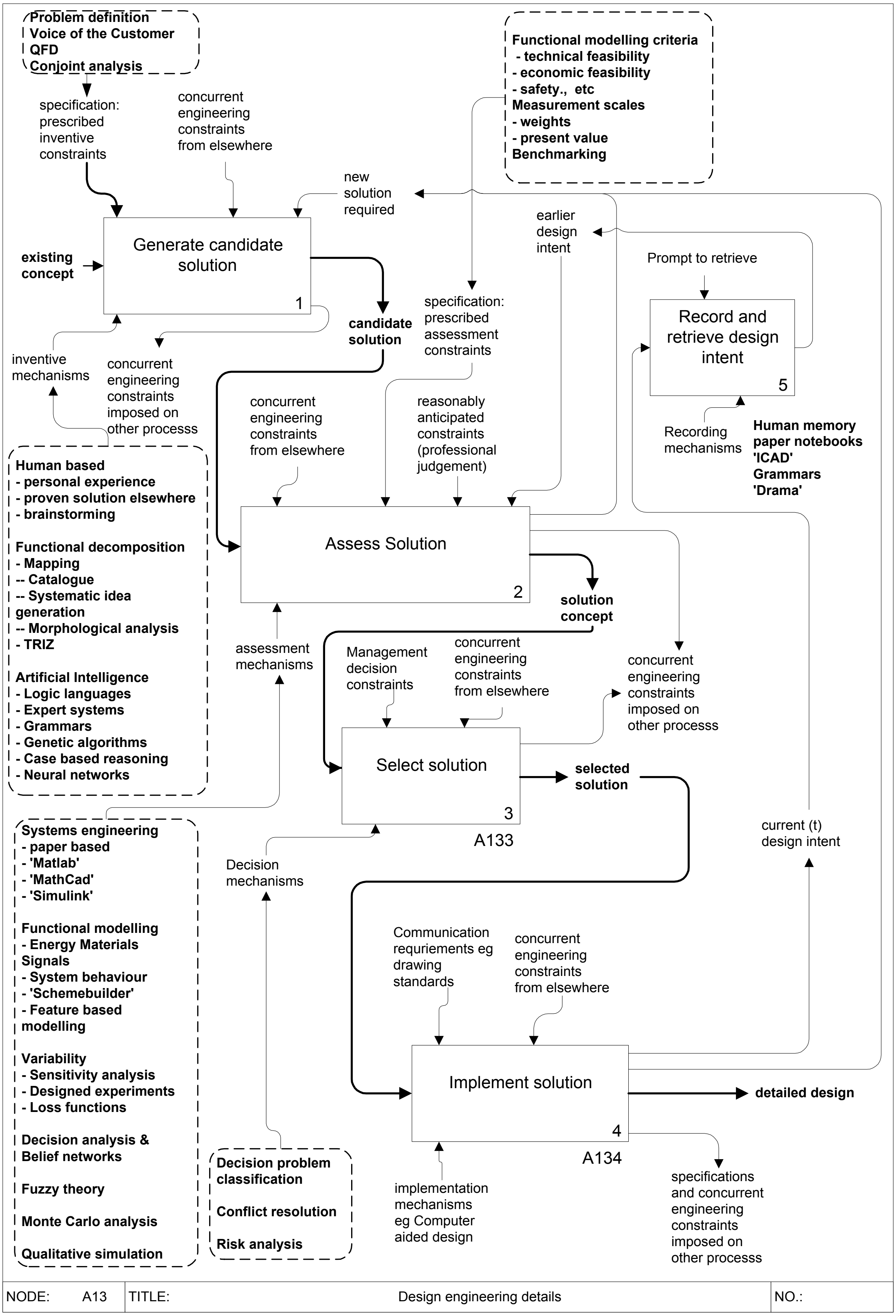


Figure 4: Generic Design Activity in the engineering design context. <A13DesignExamples.wmf>

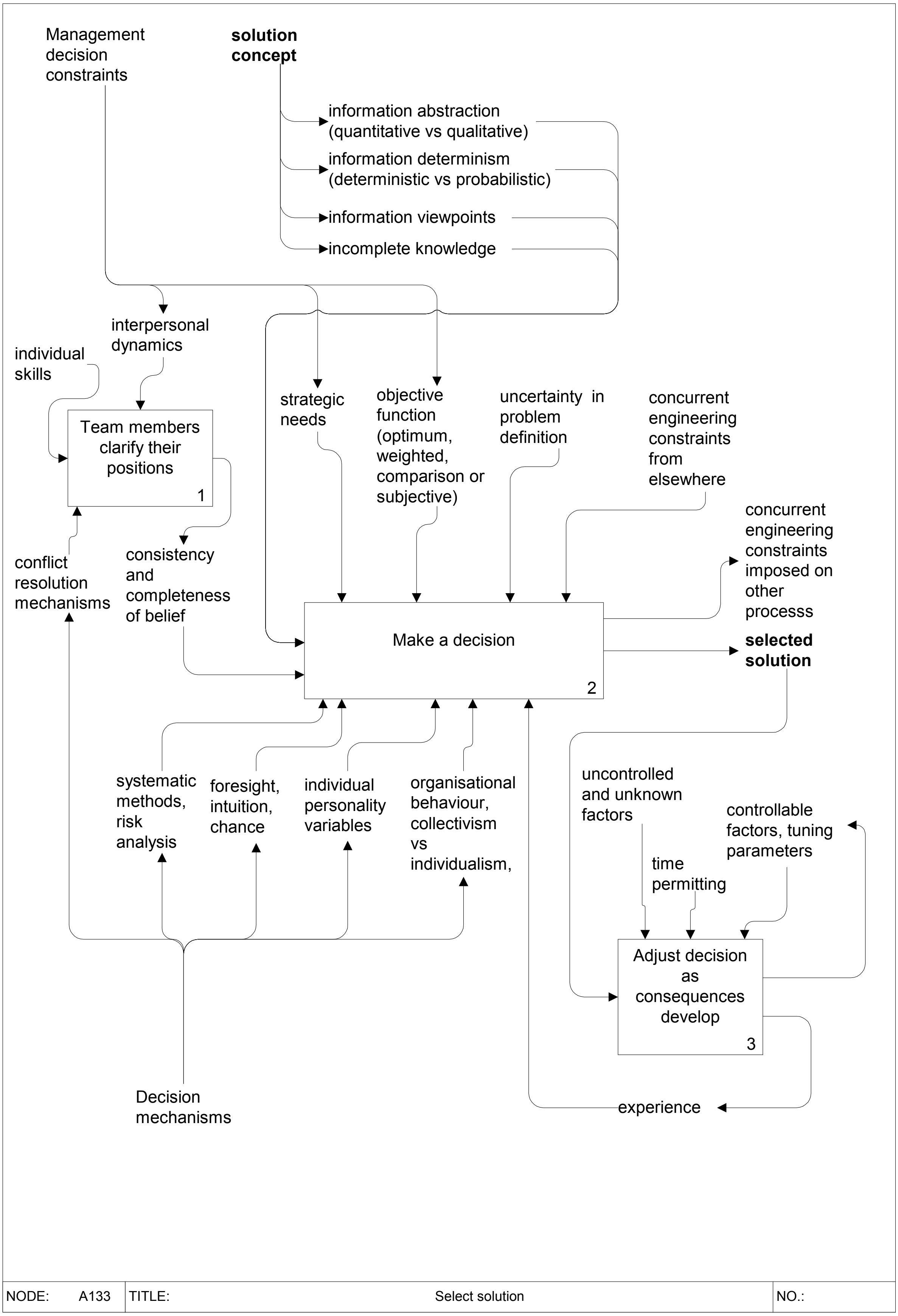
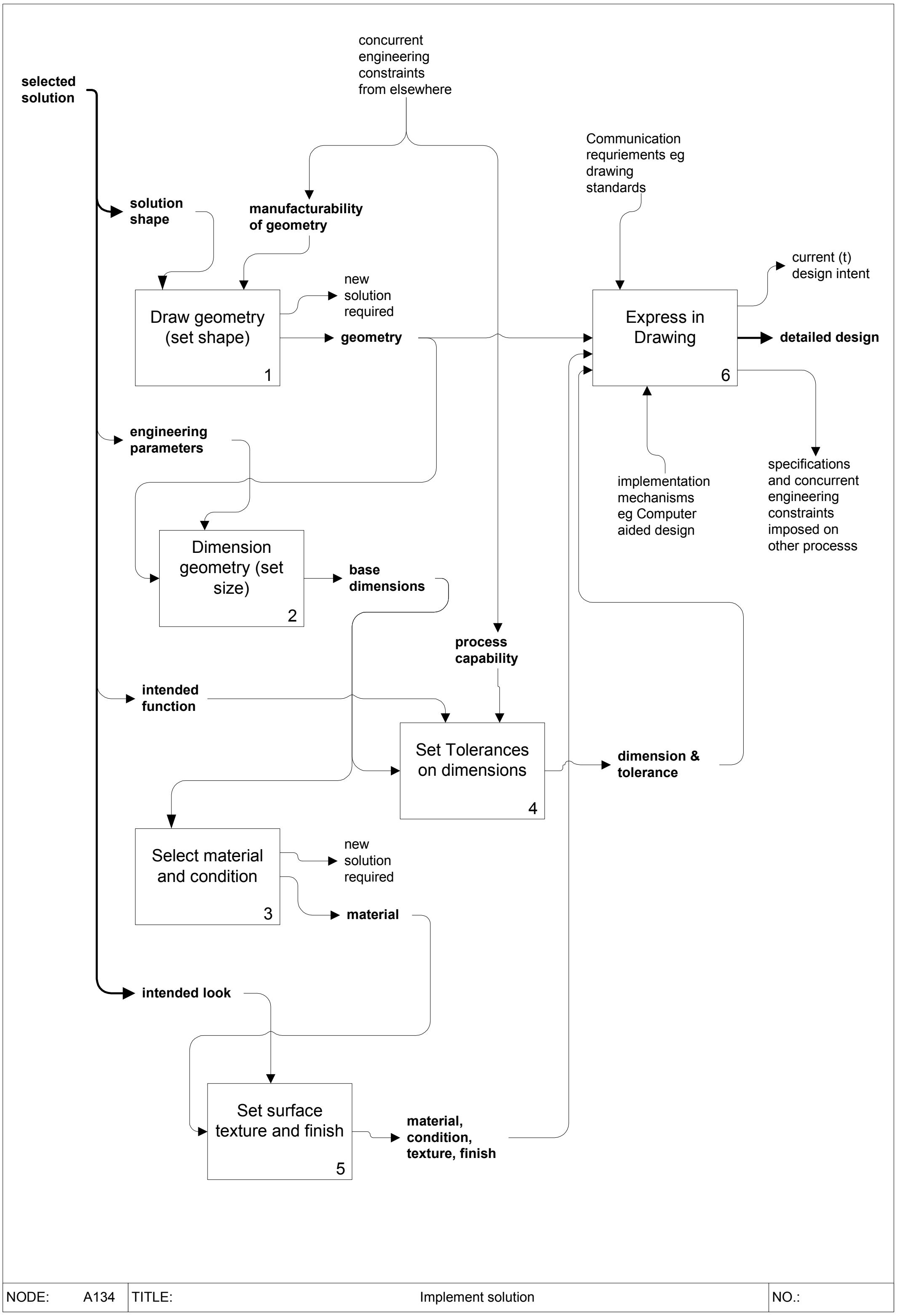


Figure 5: Model of the decision process, in particular the influences on a designer or design manager who is selecting a solution. <A133SelectSolution.wmf>



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