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Foreword

The International Journal of Systematic Innovation provides a unique international forum that can enable research and development of systematic innovation (SI) for problem solving and identification of innovative opportunities. The Journal's mission is to gather researchers, industrial practitioners, and students to share theoretical and technological advances in SI which include TRIZ, non-TRIZ human-originated systematic innovation as well as nature-inspired systematic innovation. In addition to research papers, the Journal commits to articles on new methodologies and developments, case studies, surveys, and tutorials on topics related to theoretical and technological advances in SI. By publishing quality refereed papers on the knowledge, tools, methods, or studies of SI, the Journal acts as a vital link between the research community and practitioners in all sections.

A special section is allocated in the current issue for the 1st International Conference on Systematic Innovation held in January 2010 in Hsinchu, Taiwan. To maintain the timeliness of publication, two of the best papers from the conference are included in this issue. More will appear in the later issue. In this issue, one regularly submitted paper have been carefully reviewed, revised, and selected under the Journal's regular publication guidelines. The other two papers have been selected from the First International Conference on Systematic Innovation. The Guest Editor and the Journal review committee invited authors of 25 most deserving papers presented in the conference to submit the extended versions of their papers. 18 papers were submitted timely. All the papers were then subject to the usual rigorous peer-review process. So far, two of the papers were rejected, four are accepted, two are published in this issue and the rest are still in the review process. The assembly of this issue has been a team effort. We want to thank the reviewers, the authors, and the committee for their tremendous help. We are confident that you will find these papers interesting and thought-provoking.

Finally, we would like to cordially invite you to submit your original papers to IJoSI electronically through the website at http://www.IJoSI.org. We'd also like to invite you to submit papers and/or participate in the upcoming 2nd International Conference on Systematic innovation to be held in Shanghai during May 25-28, 2011. For details, please check out http://www.icsi-conf.org. Any feedback, please send email to editor@systematic-innovation.org.

Prof. D. Daniel Sheu, Editor-in-chief
Prof. Jiahn-Horng Chen, Executive Editor
Prof. Keh-Jeng Chang, Guest Editor
July 2010 in Hsinchu, Taiwan

Connecting Real IP Value To Business Strategy

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Abstract

The paper begins with the hypothesis that current citation-based and classification code based patent search techniques offer little if any value to organizations in terms of either locating disruptive threats or opportunities, or providing leaders with forward looking strategic information. The paper goes on to discuss how the findings of the three-million data-point TRIZ/Systematic Innovation research have uncovered findings capable of addressing a forward-looking, predictive search and analysis capability that allows inventors and problem solvers to assess the likely value of a patent application before it is filed.

Keywords: IP, Inventive Principles, Business Strategy, TRIZ

1.Introduction

Ever since organizations have been subject to legal obligations to report the value of their intangible assets, a seeming industry of IP values has emerged. Understandably, in any industry, the initial ways in which value are measured are crude. Quite sensibly in the case of IP, the manner in which, for example, patents are filed lays open many decades of historical data that can be used to build ways and means of correlating between IP holdings and financial value. Thus it was found that there is a strong correlation between the number of times a given patent is cited by other later patents in the same industry domain and the value of that patent [1,2]. Almost all IP valuation methods thus become focused on this kind of historical analysis.

Given the inevitably slow patent process, the citation process is only able to start one or two years after a patent is filed. And then, because patent lawyers use a rigorous classification structure, a link between one patent and another is only deemed relevant if the two exist within the same internationally agreed classification codes. The big problem this in turn causes is that it completely fails to take into account that nearly every disruptive innovation comes not from a current competitor with an R&D team inventing solutions in a race with yours, but from someone outside your industry who realizes that their solution better serves the functional needs of your customer [3]. The detergent industry, to take a likely up and coming example, busy citing other detergent patents, will be disrupted by a textile industry player that creates self-cleaning fabrics.

The IP valuation industry is built on not just inadequate but the wrong foundations. From a business strategy perspective it is no wonder that the IP function is almost completely divorced – no leader can sensibly run their business with data that is two years out of date and blind-sided to disruptive threat. A patent deemed to have a multi-billion dollar value one day may overnight become worthless when a disruptive jump occurs, but the IP valuation team won't know it's happened until long after it is too late.

Back in the year 2000, the authors initiated a research program to overcome these inbuilt and fundamental problems with the IP valuation industry [4, 5]. Our focus was on building tools and measures for the strategists in the boardroom. Our motivation was to enable leaders to answer the following questions:

1) How much is my IP portfolio currently worth?
2) How will its value change in the coming months and years?
3) What are the disruptive threats that could appear from other industries, what impact could they have on mine, and what do I need to do about it?
4) What are the possibilities for me to exploit my existing IP into other industries?

In simple terms, it was all about giving leaders the ability to drive their business by looking through the windscreen rather than the rear-view mirror.

As it happens, ten years after the start of the research, the past can do a lot to help inventors to predict the future. Study over three million innovation data-points, as we now have, and you begin to see that the future is very highly predictable. Or rather it is provided the story is split into two parts: where and when. Knowing *when* a given technology jump will happen in the future is very difficult, but knowing *where* is governed by directions that are as close to laws as we're ever likely to get. Importantly then, if we know the where, we have the possibility to create the IP that gives us much more control over the when. Let's have a look at both sides of the where/when story in more detail.

2. THE FUTURE 'WHERE'

One of the simplest ways to spot patterns in the evolution of technical systems is to arrange solutions that deliver the same function in chronological order. The following example shows what happens when we do this for a computer keyboard (Figure 1):

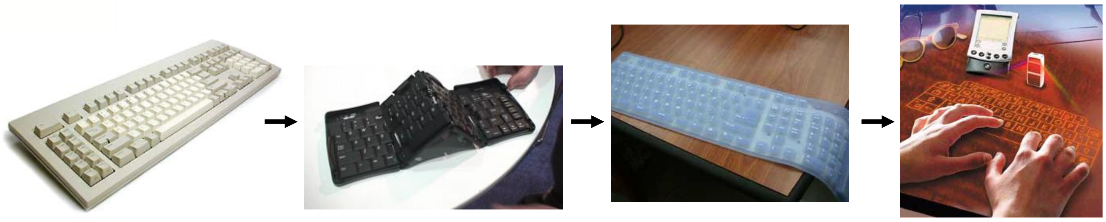

Figure 1: Evolution Of Computer Keyboard

Another example does the same for the function cutting (Figure 2). Each of the stages shown in the chronological progression represents a step-change evolution in the delivery of the function. And while the systems on the left of the progression might still exist, the value very definitely migrates from left to right, with, at each stage, some kind of conflict having to be solved. So, in the evolution of 'cutting', the various stage jumps in turn tackle problems of speed, accuracy, tool-wear and flexibility of use/elimination of waste.

Figure 2: Evolution Of 'Cutting' Technology

Repeat this kind of analysis a few thousand times and a pattern very clearly emerges. It looks something like the progression shown in Figure 3:

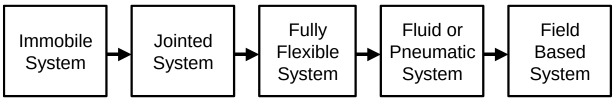

Figure 3: 'Dynamization' Evolution Trend

It is a trend describing how technical systems become progressively more 'dynamized'. It turns out to be one of thirty seven other similar trend patterns, each describing a different aspect of how systems have evolved [6]. The big advantage this offers is that if we take our own system – say we are designing the wing of an aircraft – and see that it is not at the end of the trend, then we immediately have a good idea where it is likely to evolve in the future. Aircraft wings are currently a 'jointed system' (second stage of the trend) and are thus highly likely to jump in the future to a 'fully-flexible' system. We can say this with some certainty because, the trend tells us, tens of thousands of other systems have solved conflicts and been successful by making exactly the same jumps.

When we examine a given system – like a wing – relative to the other trends that the research has uncovered, we can very quickly derive a snapshot view of how far that system has evolved in terms of some kind of universal 'evolution potential' measure. In our research, we tend to draw such evolution potential maps in the form of a radar chart [7]:

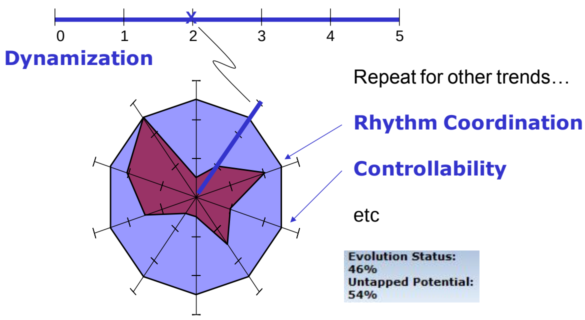

Figure 4: Evolution Potential Radar Plot Construction Method

3. THE FUTURE 'WHEN'

Knowing where things will evolve in the future represents a good start in terms of an IP valuation capability, but in order to give sensible strategic information, we also need to be able to acquire an objective means of assessing the when. The outcome of our research into this timing question has revealed two key factors:

1) How quickly the industry has been jumping in the past, and,
2) How many hierarchical levels exist between the current system type and a future 'ideal' state.

We can examine the second of these two by looking at how the forces of competition drive all industries towards more ideal solutions. The following example examines evolution within the laundry industry (Figure 5). On the left of the picture are the three main industry players together delivering the function 'cleaned clothes'. On the far right hand side is the ultimate solution – the function gets delivered (i.e. the clothes get cleaned in this case) with zero cost and zero negative side effects. The ultimate solution – except if you earn a living making detergent or washing machines – is that the clothes clean themselves. The moment consumers are convinced that such a solution actually works, inherently there is no place for either detergent or washing machine anymore. In such a world – which, thanks to the competitive pressures within the textile industry, is not too far away – the future value of detergent or washing machine IP rapidly tends to zero.

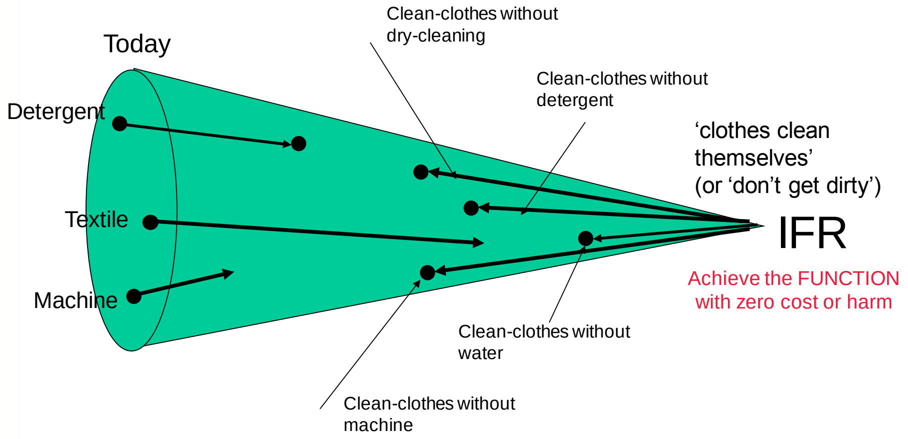

Figure 5: Players And Evolutionary End-Point Of Laundry Function

The main point here is that, as illustrated by the cone in the picture, system evolution is convergent, and in a convergent world there are inevitable losers. And moreover given a choice between detergent, machine or textile, it is extremely clear that there is a hierarchy with textiles at the top, then machines then detergents. A washing machine that cleans clothes without detergent is likely to displace even the best detergent, just as, in turn, even the best washing machine will not prevail over a self-cleaning textile fabric. As is usually the case, the threats to an industry tend to come from outside the industry.

It is relatively easy to construct this kind of conical evolution map for any industry in order to establish the hierarchy of winners and losers. What we still haven't worked out at this stage is *when* a player is likely to take-over a player lower down the hierarchy. The timing calculation is long and involved, depending to a high degree on the whims of the end customer [8, 9]. We can, however, make a significant step towards the timing answer by examining the rate at which an industry has been making jumps in the past.

The way we do this involves the evolution potential concept again. Only to obtain timing information, it is necessary to see how quickly systems at each hierarchical level are making jumps along each of the trends (Figure 6):

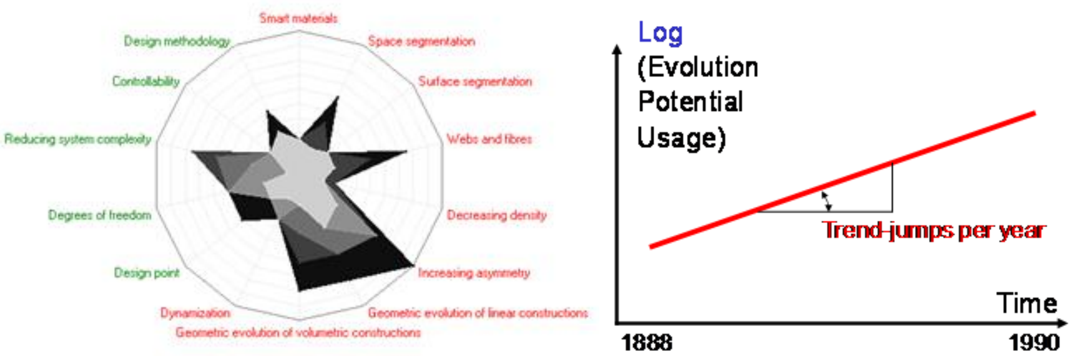

Figure 6: Evolution Potential And Relation To Innovation Timing

Knowing then that, say, the textile industry can be expected to make a step-change jump every five or so years (not quite this simple since we typically have to draw the jump-rate picture on a logarithmic scale), then we have a much clearer idea of how much longer the washing machine and detergent industries have before they become redundant.

4. TOWARDS A FUTURE-FOCUSED IP QUALITY MEASUREMENT CAPABILITY

The above tools and measurement methods provide an objective means of calculating the likely ‘where’s and ‘when’s of an industry and the IP held within that industry. The calculation, however, still requires a deal of creative thought and involved analysis. A typical analysis for an IP family will take around 4-6 weeks to answer the questions detailed earlier in this paper. The process is made possible thanks to having a database of three million radar plots and previous analyses, but it is not exactly an interactive analysis that permits live scenario planning activities to take place.

In order to solve that particular problem, we have built a number of fully automated IP value assessment algorithms built on the findings accrued from the three million data-points. Because the measurement needs to be future-focused rather than historical, we have considerably down-graded the significance of traditional measures of IP quality like citations, classifications and litigation. Instead, we have built search tools that take advantage of evolution trend information like the earlier ‘dynamization’ trend [10]. By searching through the IP database looking for functional use of key words like ‘joint’, ‘flexible’, ‘pneumatic’, ‘field’, etc it is possible to rapidly assess the maturity and number of jumps that a current solution hasn’t made yet. A more comprehensive set of search terms, emerging from the other trends is provided in the Appendix.

The output from the machine assessment measures IP against two important dimensions; the first looking at its current strength; the second looking at future potential:

Current Value Index – in this dimension we mine, for example, patent text looking for key-words that make the solution easy to circumvent. We have also identified a number of other correlating ‘strength’ factors such as number of independent Claims, length of Claim text, presence of quantified data, etc.

Future Value Index – this dimension very specifically uses the aforementioned trend keywords, but we also make a TRIZ-based (subject-action-object) semantic search looking for function words in order that we can establish a hierarchical position of the IP under investigation relative to a universal hierarchy of functions.

The resulting output is typically plotted as shown in Figure 7.

The plot divides the IP world into four distinct domains:

Duds – these are the solutions that deliver little or no value to the organization either currently or in the future, and as such are candidates for not spending more money preserving.

Rembrandts – are solutions that have little current value, but have potentially high value in the future due to the possibility that the technology may be transferred to other domains, or the solution is likely to take over the function of something lower in the universal function hierarchy.

Blindsiders – these are simultaneously the most valuable of an organizations current assets, but due to their low future value index are the ones most likely to blind-side an organization to future disruption by alternative technologies or higher level functional solutions

Stars – these are the solutions with both a high current and future value index. These are patents that are particularly well written and have anticipated as many of the future trend jumps as are achievable with current capabilities.

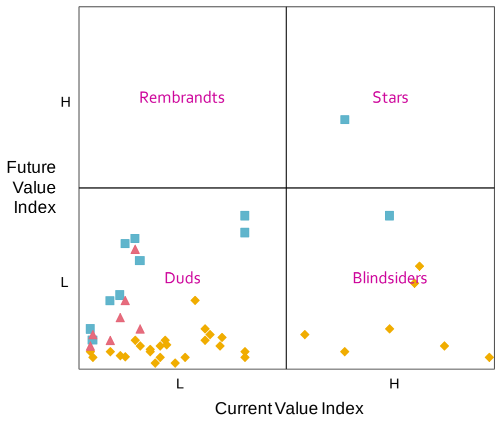

Figure 7: Current/Future IP Value Measurement Framework

The main purposes of the output is to first of all benchmark the IP of different players within an industry, or within a certain function. Looking within the portfolio for an organization, it is then aimed at providing portfolio management information – which are the things that can be dropped, ring-fenced or nurtured for example. Because the analysis is forward looking, its biggest value comes when used in conjunction with the trend information. In this role, it becomes possible for inventors and IP generators to assess the Future Value Index of a patent application before it is submitted. In this way, a piece of IP with a low score can be identified early and the inventor is able to look at the un-exploited trend jumps and determine which should then be incorporated into the invention disclosure.

It is still early days for this kind of forward-looking IP measurement tool, and as such the algorithms are still being optimized over the course of a series of client engagements. Readers are invited to explore the tool at [11]. Even in its current form, however, we believe that it already delivers previously unheard of levels of strategic capability to leaders. Just as we might not like what we see when we look through our windscreen, it has to be a better way of driving than spending the whole time looking in a rear-view mirror.

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APPENDIX

	Trend/Principle	**Patent Search Words**
1	Segmentation	split, segment, multi-, constituents, divide,bi-furcate, staged, nano, micro, particle, powder
2	Taking Out/Separation	separate, extract, remove, comparator
3	Local Quality	local, rib, protrusion, groove, channel, non-homogenous, (non-)uniform, isolate, keyway, zonal, hierarchical, gradient, layer, differential, partial, window, nano, micro, (up/down)stream, logarithmic, rough, smooth, spot
4	Asymmetry	asymmetry, Poke-Yoke, ergonomic, unequal, eccentric, cam, directional
5	Merging	merge, integrate, combine, multi, mix(er), blend, bi-, tri-
6	Universality	universal, standard, ISO, BS, Def Stan, plug, socket, protocol, language
7	Nested Doll	nest, telescopic, sleeve, hierarchical, retract, stack, tunnel
8	Counter-Weight	(counter-)balance, lift, buoyancy, aero-, hydro-
9	Prior Counter-Action	sequence, buffer, pre-, prior, preliminary, partial, mask, reverse, retard, expend, deform, surge, choke
10	Prior Action	prior, preliminary, partial, pre-, early, late, sequence, reverse, post, store, temporary
11	Beforehand Cushioning	emergency, back-up, relief, spare, temporary, (non-) linear, fail, graceful, benign
12	Equi-Potentiality	equal, balance, tension, spring, pre-, flow, compress, release
13	Other Way Around	reverse, opposite, unconventional, surprising, unexpected, upside-down, inside-out,
14	Curvature	curve, spiral, rotary, circular, twist, centrifugal, fillet, radius, helical, parabolic, hyperbolic, screw, sphere, orbital, ball, arch, dome, conical, flare, spin, vortex, cyclone, coil
15	Dynamize	dynamic, stationary, design-point, optimize, variable, flexible, rigid, stiff, relax, free, adapt
16	Slightly Less/Slightly More	over-, under-
17	Another Dimension	non-planar, conical, frusto, serrate, scallop, stack, (re-)orient,
18	Vibration	vibrate, ultrasound, resonance, hammer, piezo-, sono-, oscillate
19	Periodic Action	pulse, pendulum, timer, frequency, variable, rhythm, mode
20	Continuity Of Useful Action	template, constant, pace, continuous, optimum
21	Skipping/Hurrying	Instant, flash, drop, critical, explode, shock, accelerate
22	Blessing In Disguise	waste, vaccine, unexpected, surprising, explode
23	Feedback	feedback, sensor, control, Fourier, monitor, proportional, integral, differential, adapt, intelligent, damp
24	Intermediary	intermediary, liner, guard, layer, (inter-)connect
25	Self-Service	self, auto(matic), intelligent, waste
26	Copying	optical, virtual, shadow, reflect(ion), UV, IR
27	Cheap Disposable	disposable, cheap, replace
28	Mechanics Substitution/ Another Sense	electrical, magnetic, laser, nuclear, optical, wireless, scent, aural, acoustic, visual, kinaesthetic, gastric, (micro)wave, field
29	Fluids & Pneumatics	fluid, hydraulic, pneumatic, gel, plasma
30	Flexible Shells & Thin	film, shell, coating, sheath, inflatable, liner, leaf, web, sail, thread, fibre

	Films	
31	Holes/Porous Materials	hole, pore, void, foam, cavity, transpiration
32	Colour Change	colour, emissivity, pattern, camouflage, IR, UV, transparent, -chromic
33	Homogeneity	Homogeneous
34	Discarding & Recovering	discard, recover, dissolve, retrieve, lost
35	Parameter Changes	pressure, temperature, concentration, viscosity (think of any parameter relevant to the subject you are interested in)
36	Phase Transition	phase, melt, boil, freeze, vapour, latent
37	Thermal Expansion/Relative Change	thermal, bi-metallic, relative
38	Strong Oxidants	oxidise, oxygen, reduction, ozone, ionize, radiate
39	Inert Atmosphere	inert, vacuum, isolate, flash, damp, absorb, retard
40	Composite Materials	composite, multi, filler, fibre, hierarchical, (inter-)layer, grid, pattern, ratio

AUTHOR BIOGRAPHY

Darrell Mann is an engineer by background, having spent 15 years working at Rolls-Royce in various long-term R&D related positions, and ultimately becoming responsible for the company's long-term future engine strategy. He left the company in 1996 to help set up a high technology company before entering a program of systematic innovation and creativity research at the University of Bath. He first started using TRIZ in 1992, and by the time he left Rolls-Royce had generated over a dozen patents and patent applications. In 1998 he started teaching TRIZ and related methods to both technical and business audiences, and to date has given courses to more than 3,000 delegates across a broad spectrum of industries and disciplines. He continues to actively use, teach and research systematic innovation techniques and is author of the best selling book series *Hands-On Systematic Innovation*. Contact Darrell Mann at darrell.mann (at) systematic-innovation.com or visit http://www.systematic-innovation.com.

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Patent Analysis for Systematic Innovation: Automatic Function Interpretation and Automatic Classification of Level of Invention using Natural Language Processing and Artificial Neural Networks

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Abstract

With advances in computing power and the processes of globalization, the analytical and engineering science skills that contribute to innovation are becoming a commodity, and the activities of research and development—and innovation—are being outsourced. These trends leave the creative and systems integrative skills of engineering design as the value-added part of innovation. This paper presents a framework to address this challenge, termed mass innovation, which can be defined as expanding and diffusing innovation activities to the general population through connecting inventors and entrepreneurs with the engineering tools and services needed to assess and realize their novel design concepts. As part of mass innovation, this paper presents the development of an approach for automatic function interpretation, and an example is given, in the context of sustainable design, of the application of automatic function interpretation and automatic classification of level of invention to a means for producing compressed earth blocks. The method for automatic function interpretation is based on text extraction, natural language processing using a parser, and semantic definition of functional requirements and design parameters. The classification of level of invention is based on a machine-learning model using inputs based on patent citation measures.

Keywords: mass innovation, functional representation, natural language processing, TRIZ level of invention

1. Introduction

With advances in computing power and the processes of globalization, the analytical and engineering science skills that contribute to innovation are becoming a commodity, and the activities of research and development—and innovation—are being outsourced. (Engardio and Einhorn, 2005) These trends leave the creative and systems integrative skills of engineering design as the value-added part of innovation. (Uchitelle, 2006) This paper presents a new framework to address this challenge by integrating engineering design and social science innovation research, termed mass innovation, which can be defined as expanding and diffusing innovation activities to the general population through connecting individual inventors and entrepreneurs with the engineering tools and services needed to assess and realize their novel design concepts. (Adams and Tate, 2009; Tate et al., 2009) The approach presented in this paper in the context of sustainable design applications. (Tate et al., 2008a; Tate et al., 2010; Tate et al., 2008b)

The goal of mass innovation may be considered as making innovators into better engineers. That is, in coming up with a design idea, potential innovators should incorporate the engineering knowledge embodied in it and its connections to prior designs in the assessment of its innovative potential. The mass innovation approach combines fast and quantifiable assessment of engineering design innovation in terms of the potential transformative impact of a design idea with means for communicating the design idea with others for engineering analysis, prototyping, manufacture, and intellectual property protection. Both assessment and communication of the design idea make use of functional descriptions of the design idea, and this paper presents initial work for the automatic generation of functional description of design ideas and application of automatic classification of the design according to the theory of inventive problem solving (TRIZ) level of invention (LOI).

The assessment of engineering design innovation in terms of the potential transformative impact of a design idea is achieved by integrating several activities as shown in Fig. 1: use of design methods for functional representation and creativity enhancement; use of natural language processing (NLP) and latent semantic analysis (LSA) for the extraction and interpretation of functional and physical data from patent databases; predicting the transformative impact of a design idea through using machine learning to identify and predict design outcomes, such as TRIZ level of invention or forward patent citation measures; and finally communication of the design idea to others for product realization through engineering analysis, prototyping, manufacture, etc. This paper focuses on the development of an approach for automatic function interpretation that is used throughout the mass innovation framework. The method for automatic function interpretation presented here is based on text extraction, natural language processing using a parser, and semantic definition of functional requirements and design parameters.

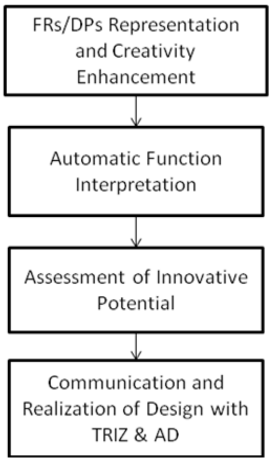

Fig. 1. Framework for Mass Innovation

Globalization and cyberinfrastructure provide new mechanisms to create opportunities for mass innovation, which is defined here as expanding and diffusing innovation activities to the general population through connecting individual inventors and entrepreneurs with the engineering tools and services needed to assess and realize their novel design concepts. The first piece of this vision is to provide fast and quantifiable assessment of engineering design innovation in terms of the potential transformative impact of a design idea. Quantifying the expected rate and breadth of adoption of new products and services remains a key uncertainty in design and development.

For sustained economic development and industrial competitiveness, participation in innovation activities needs to be broadened. The future of the innovation process should provide opportunities for individuals—especially expanding opportunities for additional individuals with or without engineering and scientific backgrounds—to participate in the genesis and realization of novel products and services. Ideas for novel products can arise from disparate sources: surgical tools and medical devices from a pathologist, sustainable building equipment from a rancher/contractor (Williamson, 2007), automotive power train components from a machinist (Dubose, 1996), a back brace from a physical therapist (McKinney, 2007), and so on. In these cases, as with all invention, an individual or small number of users have perceived unmet needs or shortcomings with existing products (Petroski, 1992), and they stand to benefit from resolving the shortcomings of the existing design or system (von Hippel, 1998; von Hippel, 2005).

The mass innovation approach seeks to provide a scientific foundation for the future of collaborative engineering designs. It is motivated by the needs of entrepreneurs and inventors and the desire to leverage cyberinfrastructure and globalization to expand and diffuse innovative activity. Once a person forms an idea, a set of computer tools should be available to state their idea formally, to assess the originality of the idea, and to quantify its prospects to have an innovative impact. Many of the pieces needed for mass innovation already exist, and others are in development. The piece that needs the most work is the first—the cyber-tools for modeling, communicating, testing, and refining of an idea to predict its innovative potential. This work is motivated by the search for the best means for non-technical individuals to formulate and develop their inventive or innovative ideas.

1.1. Sustainable Design

Sustainable design can be defined as incorporating larger environmental, resource, and social issues into decisions of the conceptualization, design, manufacture, operation, and end-of-life of products and systems. These larger issues include, for example, environmental concerns, energy independence, economic viability, and social impact. Sustainability as applied to engineering design is perhaps best understood in terms of energy resources, environmental issues, economic factors, and social impact. It is difficult for individual engineers to be conversant with the many technologies, social, and economic focuses bearing on new designs, and it is also difficult for engineers to define the right problems to be addressed (Tate et al., 2007). Radical, transdisciplinary approaches are needed for product conceptualization, development, and business models that incorporate environmental profiles, manufacturing processes, emissions, and resource consumption to achieve order-of-magnitude improvements (Ertas et al., 2000; Gumus et al., 2008; Tate et al., 2007). The example discussed in this paper is that of a means for producing compressed earth blocks (CEBs).

Earth can be formed into walls using dried mud bricks (adobe), dried poured earth, rammed earth, and compressed earth blocks. With rammed earth, forms are first built similar to cast-in-place concrete forms, and earth is then added in shallow layers and rammed. Compressed earth blocks are defined as earthen blocks created by means of compression in hand-operated or hydraulic machines. (Eko et al., 2006) Currently commercially available CEB machines make blocks up to about 25 x 35 x 10 cm which are stacked to form a wall. (Advanced Earthen Construction Technologies, 2009) Stabilizers such as Portland cement, lime, gypsum, and others can be used along with the soil in the blocks; however, in some cases, stabilization can also be achieved physically without chemical additives by using compaction and granular stabilization. (Burroughs, 2001; Minke, 2006) The Texas Tech University Whitacre College of Engineering and TTU College of Architecture have been working with EarthCo Building Systems to develop a comprehensive building system for efficient and low-cost manufacture and placement of earthen building envelopes using large-scale compressed earth blocks (CEBs). By scaling up the production and placement of CEBs, manual labor and production time can be minimized, and CEB technology can be made cost competitive with traditional building technologies. (Tate et al., 2008a; Williamson, 2007)

1.2. Functional Description of Design Intent

Formal methods used for representing functions during problem formulation describe a system's functions and how they interact. (Antonsson and Cagan, 2001; Chakrabarti, 2002) They are intended to facilitate communication among designers and stakeholders, build group consensus, and support the development of innovative and collaborative designs. (Hirtz et al., 2002) Problem formulation has been observed to be the most difficult task in design (Suh, 1990), and it is critical because design programs and designed artifacts will fail if problem formulation never stabilizes or is based upon incorrect premises. Recent research in engineering design has started with a "functional basis" for representing engineering designs, yet this is only one of many approaches to modeling function that have been proposed. (Antonsson and Cagan, 2001; Chakrabarti, 2002) The approaches to representing function can be divided into two categories—(1) "functional basis" or "black box" approaches that trace various flows through a system (typical examples include functional basis (Altshuller, 1984; Pahl and Beitz, 1996; Stone et al., 2002; Stone and Wood, 2000), black box, and structured analysis and design technique (SADT) (Marca and McGowan, 1993; Ross, 1977; Ross, 1985)) and (2) those that alternate between functions and physical means, progressing from systems to components to create a hierarchy of functions (for example, function means tree (FMT) (Andreasen et al., 1995; Andreasen and Hein, 1987; Hubka and Eder, 1992) (compare with (Marples, 1961) and (Suh, 1990; Suh, 2001)), enhanced FMT (Johannesson, 2004), Gero's function—behavior—structure (FBS) ontology (Dorst and Vermaas, 2005; Galle, 2009; Qian and Gero, 1996), and SysML (Hause et al., 2005)). Recent publications by Erdena et al. and van Eck et al. have compared and contrasted prominent approaches to functional modeling. (Erdena et al., 2008; van Eck et al., 2007) In this paper, the second type of approach will be followed that alternate between functions and physical means in a hierarchical manner.

Data mining should be useful for mining repositories of design intent (patents, electronic design notebooks, etc.) as noted at several NSF-sponsored workshops. (Kusiak, 2007; Schunn et al., 2006; Shah et al., 2005) Engineering design researchers have proposed or developed databases for searching for physical means to provide functionality, and several approaches to engineering design innovation incorporate the use of databases for stimulating or documenting conceptual engineering design. Early efforts to systematize engineering design information in repositories include design catalogs by German researchers (see examples in (Pahl and Beitz, 1996)), morphological analysis (Norris, 1962; Pahl et al., 2007; Zwicky, 1969), and a database of physical effects included as part of TRIZ. (Altshuller, 1984; Fey and Rivin, 2005; Savransky, 2000) More recently the biomimetic approach of Tinsley et al. uses a repository for storing biological functions that can serve as stimuli for engineering designers. (Tinsley et al., 2007) Work by Wood and colleagues proposes a design by analogy method to create transformative designs (defined as changing state or configuration to provide new functionality) (Skiles et al., 2006). Yang has investigated data mining of electronic design logbooks and the development of thesauri for retrieving design information. (Yang et al.,

2005) A challenge of repository-based approaches is the effort required to populate the repository as well as efforts to ensure consistency, usefulness, and uniqueness of the information stored within the repository. This work addresses data mining of design intent using natural language processing from a large repository of U.S. patent documents. One of the outputs of this work are expected to be sets of functional and physical design data, organized by discipline, that can be used in populating design repositories.

1.3. Automatic Function Interpretation

The goal of engineering design is to create a product that can carry out certain tasks in order to satisfy the needs of customers (Hirtz et al., 2002; Suh, 1990). Modern marketing has been rephrased as (1) discovering needs and wants of its target customers, and (2) satisfying these needs in a better way than competitors (Wagner and Hansen, 2004). Typically, customer needs can be obtained by gathering market data and by analyzing these data with techniques such as customer analysis, product research, competitor analysis, trend forecasting, risk analysis, etc. However, this approach is both time-consuming and costly. To reduce potential cost, researchers may take the advantage of computational approached to interpret design intention by means of natural language processing (NLP) techniques and axiomatic design theories. The former is widely used for text understanding and text generation while the later provides a framework for representing solutions in terms of explicitly stated functional requirements (FRs) and design parameters (DPs) (Suh, 1990).

Given a description of an engineering design, such as given in a patent document, functional requirements (FRs) and design parameters (DPs) can be extracted by taking advantage of a computational linguistic model. Extracted FRs and DPs not only serve as source of inspiration for designers but also help designers focus on fulfilling customer needs (CNs). In order to rank FRs and DPs extracted from design descriptions, assessment of innovative potential is carried out to classify the level of invention.

1.4. Assessment of Innovative Potential and TRIZ

Goel and Singh (1998) suggest that product design is a goal-directed problem-solving activity that relies heavily on creative thinking, drawing analogies with related knowledge, and experience. Also, they indicated that this work should be done by integrating creativity and innovation tools with engineering design methods. However, there is still a remaining question: How can the innovative potential of a design be measured? The answer to the question above is TRIZ metrics such as degree of ideality and level of invention (Fey and Rivin, 2005). TRIZ provides a systematic process to define and solve given problems which helps increase creativity. In TRIZ, there are five level of invention. The relative percentages of the five level of invention are given in Table 1 (Clausing and Fey, 2004; Fey and Rivin, 2005; Savransky, 2000).

These levels of invention are based on a combination of the resolution of engineering contradictions and interdisciplinarity—borrowing of a solution from another discipline. These levels of invention are based on the resolution of system conflicts (or functional coupling) through transdisciplinary approaches (Altshuller, 1984; Fey and Rivin, 2005). In a previous paper, Adams and Tate demonstrated the use of natural language processing for patent data and the use of a neural network model to estimate the TRIZ level of invention and TRIZ level of ideality for patents. (Adams and Tate, 2009) Adams (2009) also predicted innovative potential by constructing transdisciplinary metrics and training an artificial neural network. He concluded that such metrics helped not only integrate new technologies but also measure the success of a design based on the levels of integration across diverse fields and different parts of a company.

Two related works for evaluating level of invention include (Regazzoni and Nani, 2008) and (Verbitsky, 2004). Regazzoni and Nani use intellectual property density, given by the ratio of number of patents over the number of International Patent Classification (IPC) 4 digit classes per year, to define a break event year that separates patents according to TRIZ level of invention ("breaking" between levels 2 and 3). They identify the LOI of a series of patents having the term "x-rays" in title, abstract, or claims. (Regazzoni and Nani, 2008) Verbitsky presents a measure of level of invention based on the actual number of citations a patent receives versus an expected number of citations, calculated based on the patent's position in a series of patents. (Verbitsky, 2004)

1.5. Communication and Realization of the Design with TRIZ and Axiomatic Design

After the originality and feasibility of a design idea are validated, the next step in the mass innovation process involves the inventor communicating the idea to others. Engineering analysis can be accomplished through a variety of means, depending on the nature and complexity of the project: doing the analysis oneself, automated analysis with software, using virtual reality and other computer-aided engineering tools, outsourcing the analysis to domestic or overseas engineers, or collaboration with academic or industrial partners. Once the design and engineering analysis have been conducted, a prototype can be created. Again this can be accomplished through several possible methods: rapid prototyping, outsourcing, etc. Within a short time—a few weeks or days—an idea should go from germination to physical implementation. The inventor can then use the physical device for experimental validation, robust design, etc.

Table 1. TRIZ Level of Invention (Fey and Rivin, 2005; Savransky, 2000)

Level	Description	% of Patents (Fey and Rivin, 2005)
Level 1	Apparent solution: A component intended for a task is used.	32%
Level 2	Small improvement: An existing system is slightly modified.	45%
Level 3	Invention inside paradigm: At least one system component is radically changed or eliminated; the problem and solution are within one discipline.	19%
Level 4	Invention outside paradigm: A new system is developed using a solution that is interdisciplinary.	<4%
Level 5	Discovery: A pioneering invention is created, often based on recently discovered phenomenon.	<0.3%

Additional steps in the entrepreneurial process to be considered include the development of business plans and strategy, quantifying the financial prospects of the design, raising capital, etc. as well as the need for protecting intellectual property and intellectual capital. These steps can be tied to existing architectural frameworks for modeling operational, functional, node connectivity, and other business and strategic aspects of a new design.

The paper is structured as follows: After the introduction, section 2 presents an overview of methods used in the framework. Section 3 presents a simple example of sustainable design centered on compressed earth block (CEB) technology, and section 4 discusses the results. Finally, conclusions and future work are given at the end of the paper.

2. Methods for Automatic Function Interpretation

In this section, the methods adopted in this paper are discussed. The importance of analyzing patents is described in the first sub-section, and the formation of FRs/DPs from a given patent follows. The last part of this section describes the evaluation approach for innovative potential.

2.1. Patent Analysis

Tseng et al. (2007) state that patent documents contain valuable information for industry, business, law, and policy-making communities. Innovative solutions, business trends, technological details, and their relationships can be revealed if careful patent analysis is made. On the other hand, a patent has highly structured content which enables researchers to carry out multiple kinds of analysis. A typical U.S. Patent includes several sections: abstract, related U.S. patent documents, references cited, claims, and description.

By manually reviewing patents, functional requirements and design parameters can be obtained from both claims and descriptions. However, the sentences in claims are usually too long for the parser which results in low efficiency, and parsing performance is also less satisfactory. Therefore, the authors chose to implement the NLP techniques on the description section, especially the summary of invention section which is high-quality abstraction of the invention that has been summarized by a human.

2.2. Text Extraction, Function Generation, and Interpretation of Design Intention

The structure of functional requirement interpretation can be divided into the three steps shown in Fig. 2. They are text extraction, natural language processing, and FRs/DPs generation. Each of these three steps interact with a local database to save or load data.

In the first step, the program downloads patents from United States Patent and Trademark Office (USPTO) website for future processing. Patent content extracted and stored locally makes future steps faster and easier than searching online repeatedly. Also, during the extraction, the content of a patent is automatically segmented into different sections by using regular expression. These sections include patent title, abstract, reference, citations received, claims, and description. Table 2 demonstrates a set of regular expressions used for extraction tasks.

The second step is to implement two NLP techniques for extracted and segmented patents stored in database. These two NLP techniques include part-of-speech (POS) tagging and probabilistic parsing. In this paper, the POS tagger and statistical parser developed by Stanford Natural Language Processing Group1 is adopted. The former technique helps clarify the identification of a word in a sentence by using maximum entropy approach (Toutanova and Manning, 2000). The tagging annotation adopted by Stanford POS tagger is from the Penn TreeBank which contains 40 different tags2. An example of a tagged sentence extracted from U.S. Patent 6736626 following the Penn TreeBank tags is shown in Table 3.

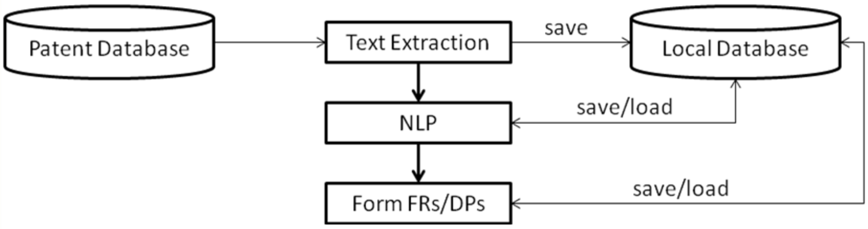

Fig. 2. Framework of Function Generation

Table 2. Regular expression used for text extraction

<table>
<tr><td>SECTION</td><td>REGULAR EXPRESSION</td></tr>
<tr><td>Patent No.</td><td><TITLE>United States Patent(.*)</TITLE></HEAD></td></tr>
<tr><td>Title</td><td>(.*)</td></tr>
<tr><td>Class</td><td>Current U.S. Class:(.*)Current International Class:</td></tr>
<tr><td>Citations</td><td><[aA][^>]*[Hh][Rr][Ee][Ff]=((\"[^>]+\")|([^>]+))>([^<>]+)</[aA]></td></tr>
<tr><td>Abstract</td><td>(<CENTER>|<B>|<I>|\\s)+Abstract(</B>|</CENTER>|</I>|\\s)+(.*)(</P>)</td></tr>
<tr><td>Claims</td><td>(<CENTER>|<B>|<I>|\\s)+Claims(</B>|</CENTER>|</I>|\\s)+(.*)<HR>\\s*(<CENTER><B><I>)</td></tr>
<tr><td>Description</td><td>(<CENTER>|<B>|<I>|\\s)+Description(</B>|</CENTER>|</I>|\\s)+(.*)<HR>\\s*<CENTER></td></tr>
</table>

According to Klein and Manning (2003), the tagger provides 97.24% accuracy on Penn TreeBank Wall-Street Journal. However, to form readable functional requirements and design parameters, single tagged words are still too ambiguous even with a given tag. Consider the simple word run as an example. According to explanations in Merriam-Webster online dictionary, the word run has 15 different meanings as an intransitive verb3. Therefore, it's extremely vague for readers if the single word instead of a phrase is used. Fortunately, the later technique, parsing, enables one to determine the grammatical structure given in a sentence. In other words, phrases can be used instead of single words in the output parse tree to eliminate the ambiguity of single words. Also, by parsing a sentence, pairs

1 http://nlp.stanford.edu/index.shtml
2 http://www.cis.upenn.edu/~treebank/
3 http://m-w.com/dictionary/run

of dependent subjects, actions, and objects (SAO) can be found. This facilitates the generation of functional requirements and design parameters in the next step. An example of the parser output is shown in Table 4. In this example, the main subject of the sentence is "The Homeland Secuirty secretary" and main action is "said". The sub-subject of the sentence is "legislative efforts" and sub-action is "will begin". As Klein and Manning (2003) indicated in their paper, the Stanford parser adopted un-lexicalized straightforward probabilistic context free grammars (PCFGs) approach that provided performance of 86.36% when the length of a sentence was less than 40 words.

Table 3. Penn TreeBank POS Tag and Tagged Sentence from U.S. Patent 6736626

Penn TreeBank Tags

CC - Coordinating conjunction	**PRP$** - Possessive pronoun (prolog version PRP-S)
CD - Cardinal number	**RB** - Adverb
DT - Determiner	**RBR** - Adverb, comparative
EX - Existential there	**RBS** - Adverb, superlative
FW - Foreign word	**RP** - Particle
IN - Preposition or subordinating conjunction	**SYM** - Symbol
JJ - Adjective	**TO** - to
JJR - Adjective, comparative	**UH** - Interjection
JJS - Adjective, superlative	**VB** - Verb, base form
LS - List item marker	**VBD** - Verb, past tense
MD - Modal	**VBG** - Verb, gerund or present participle
NN - Noun, singular or mass	**VBN** - Verb, past participle
NNS - Noun, plural	**VBP** - Verb, non-3rd person singular present
NNP - Proper noun, singular	**VBZ** - Verb, 3rd person singular present
NNPS - Proper noun, plural	**WDT** - Wh-determiner
PDT - Predeterminer	**WP** - Wh-pronoun
POS - Possessive ending	**WP$** - Possessive wh-pronoun (prolog version WP-S)
PRP - Personal pronoun	**WRB** - Wh-adverb

Sentence before tagging: The press foot is then lowered to a second level in the breech to receive a volume of the loose earth from the feed drawer into the breech.

Sentence after Tagging: The/DT press/NN foot/NN is/VBZ then/RB lowered/VBN to/TO a/DT second/JJ level/NN in/IN the/DT breech/NN to/TO receive/VB a/DT volume/NN of/IN the/DT loose/JJ earth/NN from/IN the/DT feed/NN drawer/NN into/IN the/DT breech./NN

The last step is to concatenate corresponding noun phrases and verbal phrases to form functional requirements and design parameters by finding keywords such as "to" or "for" in verbal phrases. The keyword "to" in verbal phrases serves as a part of an inifitive to express design intention, and the keyword "for" in verbal phrases also express the intention to carry out a certain task. Therefore, by combining the verbal phrases and corresponding objectives, functional requirement can be formed as shown in Table 5. The subject of the sentence is the design intention for implementing designated tasks. Thus, it will be the design parameter for fullfiling funtional requirements that have just been defined before.

Table 4. Example of Parsing Output using Stanford Parser

Sentence to be parsed: A press foot is raised in a breech to a first level even with an open upper end of the breech.

Parsing Tree:

```
(ROOT
 (S [137.482]
  (NP [25.250] (DT [4.555] A) (NN [7.572] press) (NN [8.896] foot))
  (VP [111.090] (VBZ [0.144] is)
   (VP [106.729] (VBN [5.600] raised)
    (PP [38.288] (IN [1.552] in)
     (NP [35.080]
      (NP [15.890] (DT [1.419] a) (NN [12.699] breech))
      (PP [18.649] (TO [0.003] to)
       (NP [15.008] (DT [1.419] a) (JJ [4.217] first) (NN [6.390] level)))))
    (PP [59.247] (RB [3.378] even) (IN [2.594] with)
     (NP [46.543]
      (NP [29.399] (DT [3.221] an) (JJ [6.991] open) (JJ [7.968] upper) (NN [6.046] end))
      (PP [16.603] (IN [0.666] of)
       (NP [15.536] (DT [0.650] the) (NN [12.699] breech)))))))
  (. [0.002] .)))
```

Table 5. Extraction of FR and DP from a Sentence

Example: The press foot is then lowered to a second level in the breech to receive a volume of the loose earth from the feed drawer into the breech.

SAOs:
Main subject: *The press foot*
Main action: *is then lowered to*
Main object: *a second level in the breech*
Sub subject: -
Sub action: *to receive*
Sub object: *a volume of the loose earth the feed drawer into the breech*

FRs: *receive a volume of the loose earth the feed drawer into the breech*
DPs: *The press foot is then lowered to a second level in the breech*

2.3. Application of Innovative Potential Assessment Metrics

The TRIZ level of invention of a patent can be estimated by using patent citation analysis. The measure of originality is calculated using the following equation (Jaffe and Trajtenberg, 2002):

$$O_i = 1 - \sum_{k=1}^{n} \left(\frac{b_k}{b}\right)^2 \qquad (1)$$

where b is the number of patents cited in current patent, and k indicates the subclass of the cited patent. For example, if one patent cites 3 patents and 2 of the patents are from subclass X and 1 patent is from subclass Y, then the originality measure is $1-((2/3)^2 + (1/3)^2) = 0.44$.

A patent's generality is measured in a similar way, but considers the forward patent citations by patents from multiple subclasses (Jaffe and Trajtenberg, 2002).

$$G_i = 1 - \sum_{k=1}^{n} \left(\frac{f_k}{f}\right)^2 \qquad (2)$$

where f is the number of patents that cite the current patent, and k indicates the subclass of the patents that cite the current patent.

By combining the number of citations made, citation received, originality, and generality measures, the input for classification can be constructed. Also, the level of invention of each patent serves as the class label in a supervised machine learning method such as an artificial neural network (ANN) or support vector machine (SVM). The training sample in the example includes 140 patents of mechanical devices with manually assigned levels of invention (Adams, 2009). Part of the training data is listed in Table 6.

3. Example of Sustainable Design Application

As mentioned earlier, the case study of this paper centers on an application of sustainable design. Compressed earth block (CEB) is a promising construction material for manufacturing building envelopes by mechanically compressing into blocks a mix of dirt, non-expansive clay, and possibly stabilizers. Since the materials for building CEBs can be all natural, the manufacturing process has minimal impact on the environment.

U.S. Patent 6736626 is an example that introduces a method for manufacturing CEBs. The first step of the case study is manually analyzing functional requirements and design parameters in the patent using axiomatic design in this section. Then, the results of implementing NLP techniques and assessment of innovative potential are presented in the following two sub-sections respectively and compared with the manual analysis.

3.1. Manual Analysis

In the description of U.S. Patent 6736626, six key components are introduced: breech, press foot, feed drawer, bucking foot, hopper, and hydraulic system. Except the hydraulic system, the other key components are marked as 10, 20, 30, 50, and 60 in Fig. 3.

By carefully analyzing the summary of invention, 15 pairs of FRs and DPs can be obtained. This result is shown in Table 7.

By further investigating these FRs and DPs, a hierarchical structure can be formed as some of FRs and DPs belong to a sub-level rather than the higher level of the design. For example, the block is formed by moving the press foot to a designated place to compress loose earth. Therefore, FR_3 and DP_3 belong to the higher level in the structure. On the other hand, the press foot is moved by a hydraulic system, thus FR_{10} and DP_{10} belong to a lower level. The detailed dependencies are described in Fig. 4.

3.2. Automatic FRs/DPs Interpretation for this Case study

According to the description in section 2, the first step for interpreting FRs and DPs is to extract patents from the USPTO web patent databases (USPTO) and save the content of patents such as title, patent number, citations, abstract, claims, and description to a local database.

Instead of implementing NLP on all the sections of patents, only the description section of a patent is analyzed with the parser and POS tagger. The reason is that the length of sentences in the claims are usually too long to be parsed and the parsing performance is not satisfactory. Therefore, this paper mainly focuses on using the two NLP techniques on the description section, especially the summary of invention.

In the last step, cause-effect relationships are searched throughout all the sentences by locating keywords such as "to" and "for". A verb is concatenated together with its object to form functional requirements, while the subject remains as the design parameter.

The programming language used in this project is the Java[4], and the Integrated development environment (IDE) is MyEclipse[5]. MySQL[6] is selected as the local database. SQLyog serves as the GUI for manipulating the local database. The running result is shown in Table 8. In total, 11 functional requirements and design parameters are extracted from U.S. Patent 6736626. As can be seen, the first functional requirement is irrelevant, and some of phrases in sentences such as the 2nd FR and 3rd FR contain mistakes that may cause ambiguity for readers.

Extending this method to several patents about compressed earth block machine, a comparison between automatic analysis and manual analysis is shown through Fig. 5 to Fig. 8. The result shows that the method adopted in this paper is strongly dependent on writing style of patent authors. As the writing style varies dramatically among different patent authors, the task of interpreting design purpose of patents becomes very sophisticated. However, the result is still encouraging as it shows the interpretation of author's design purpose is feasible with the support of NLP techniques.

Table 6. Example of Level of Invention Training Data (Adams, 2009; Adams and Tate, 2009)

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[4] http://www.java.com/en/
[5] http://www.myeclipseide.com/
[6] http://www.mysql.com/

Patent #	Citation made	Citation received	generality	originality	Level of Invention
4118531	11	190	0.86	0.82	2
4367924	2	401	0.85	0.50	4
4310440	7	213	0.84	0.48	5
4031519	24	47	0.84	0.84	4
4194041	12	163	0.83	0.66	3
3229759	1	20	0.83	0.00	4
5143854	34	162	0.82	0.88	2
4049997	5	20	0.81	0.38	1
3702886	1	382	0.81	0.00	3
3906324	10	19	0.80	0.48	1
4230463	24	223	0.80	0.73	2
4063271	5	20	0.79	0.32	1
4440871	14	273	0.77	0.74	3
4907340	27	19	0.77	0.70	3
5053074	9	8	0.75	0.59	3
4133814	4	219	0.74	0.50	5
4983886	8	19	0.73	0.53	1
4688900	51	171	0.71	0.77	3
4036012	5	9	0.70	0.63	3
4060023	5	7	0.69	0.44	1
4399209	15	231	0.68	0.27	2
3753145	1	20	0.67	0.00	4
4061724	1	202	0.62	0.00	5
4072541	8	20	0.62	0.24	1
4706216	1	194	0.61	0.00	5
5109824	6	7	0.57	0.48	2
4265990	2	202	0.52	0.00	5
5108350	22	12	0.51	0.59	2
5108349	3	2	0.50	0.67	1
4435047	19	192	0.49	0.83	2
4061389	9	3	0.44	0.44	1
4491628	12	170	0.44	0.28	2
4060980	7	20	0.42	0.41	1
4380635	4	174	0.33	0.63	2
4035047	8	20	0.32	0.22	1
4100324	7	261	0.32	0.63	4
3982201	3	33	0.27	0.00	3
5274650	5	10	0.18	0.48	2
5572914	3	1	0.10	0.00	1

3.3. Estimation of Innovative Potential for this Case Study

The prediction is made by taking advantage of Matlab Neural Network Fitting Tool (abbreviated as nftool). The network is a two-layer feed forward network with 20 hidden neurons in hidden layer, and the training algorithm is back-propagation. 147 training samples are divided into 3 parts: 70% of them are used for training purpose, 15% of them are used for validation, and the remaining 15% of them are used for testing. The training completes in 33 iterations with 0.067 mean square error on validation sample.

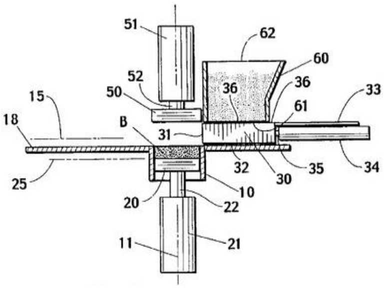

Fig. 3. Proposed CEB Manufacturing Machine from U.S. Patent 6736626[7]

Table 7. FRs/DPs from Manual Analysis

[7]http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PALL&p=1&u=%2Fnetahtml%2FPTO%2Fsrchnum.htm&r=1&f=G&l=50&s1=6736626.PN.&OS=PN/6736626&RS=PN/6736626

- FR_1: receive a volume of the loose earth
- DP_1: the press foot is then lowered to a second level in the breech
- FR_2: remove or screed the excess loose earth
- DP_2: feed drawer is withdrawn laterally across the planar surface
- FR_3: compress the loose earth in the breech
- DP_3: the press foot is raised to a third level in the closed breech
- FR_4: permit vertical ejection of the block
- DP_4: The bucking foot is then raised to a level higher than the top of the feed drawer
- FR_5: refill the feed drawer
- DP_5: feed drawer will be aligned under a hopper storing loose earth
- FR_6: push the previously-made block
- DP_6: abutment of a three dimensional face of the previously-made block with a leading face of the feed drawer
- FR_7: open and close the upper end of the breech
- DP_7: bucking foot is aligned above the breech for vertical reciprocal movement along the Z-axis
- FR_8: move the feed drawer across a surface coplanar
- DP_8: a hydraulic cylinder
- FR_9: move the bucking foot
- DP_9: the second hydraulic cylinder
- FR_{10}: move the press foot
- DP_{10}: the third hydraulic cylinder
- FR_{11}: provide the lateral tongue-and-groove of the block
- DP_{11}: the breech is substantially rectangular in the X-Y plane with two-dimensional surfaces in its Y-Z side walls and complementary three-dimensional surfaces
- FR_{12}: provide the vertical tongue-and-groove of the block
- DP_{12}: the press foot and the bucking foot have complementary three-dimensional surfaces in their upper and lower X-Y walls
- FR_{13}: close the hopper
- DP_{13}: trailing plate coplanar with its open upper end
- FR_{14}: pass over the three dimensional surface
- DP_{14}: feed drawer has a fixed wall with a lower edge notched
- FR_{15}: screed along the open upper end of the breech
- DP_{15}: hinged wall following the fixed wall with a level lower edge

Table 8. Automatic Generated FRs and DPs from U.S. Patent 6736626

1st FR is: making a block pressed earth
1st DP is: accordance with the invention a method is provided

2nd FR is: receive a volume of the loose earth the feed drawer the breech
2nd DP is: The press foot is then lowered to a second level in the breech

3rd FR is: remove or screed the excess loose earth the open upper end of the breech
3rd DP is: The feed drawer is withdrawn laterally across the planar surface out of registration

4th FR is: close the upper end of the breech
4th DP is: A bucking foot is then lowered

5th FR is: compress the loose earth in the breech a block
5th DP is: The press foot is raised to a third level in the closed breech

6th FR is: permit vertical ejection of the block the open upper end of the breech the lateral path of the feed drawer
6th DP is: The bucking foot is then raised to a level the top of the feed drawer

7th FR is: refill the feed drawer
7th DP is: additional loose earth will be dispensed from the hopper

8th FR is: open and close the upper end of the breech
8th DP is: The bucking foot is aligned above the breech for vertical reciprocal movement along the Z-axis

9th FR is: receive a volume of loose earth
9th DP is: the loose earth the breech against the bucking foot form a block of pressed earth

10th FR is: provide the lateral tongue-and-groove of the block
10th DP is: the breech is substantially rectangular in the X-Y plane with two-dimensional surfaces in its Y-Z side walls and complementary three-dimensional surfaces in its X-Z side walls

11th FR is: provide the vertical tongue-and-groove of the block
11th DP is: All preferably , the press foot and the bucking foot have complementary three-dimensional surfaces in their upper and lower X-Y walls , respectively

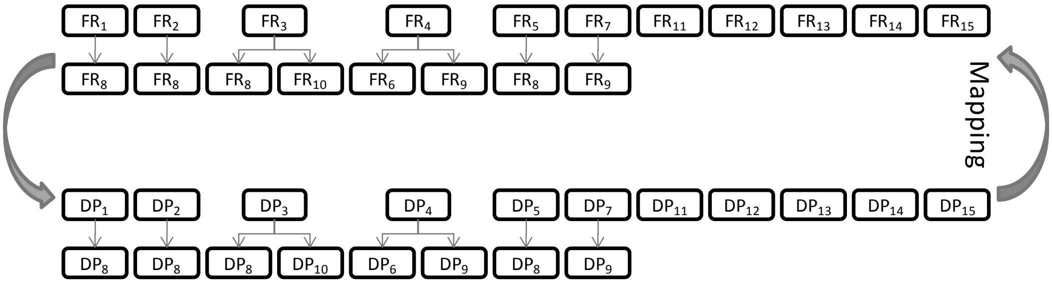

Fig. 4. FRs and DPs in a Hierarchical Structure

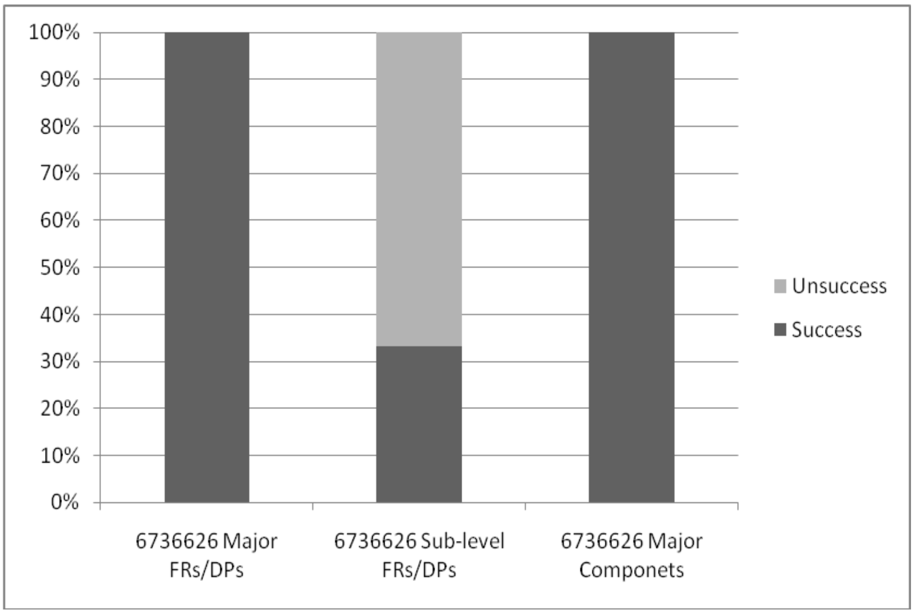

Fig. 5. Comparison between manual analysis and automatic analysis of U.S. Patent 6736626

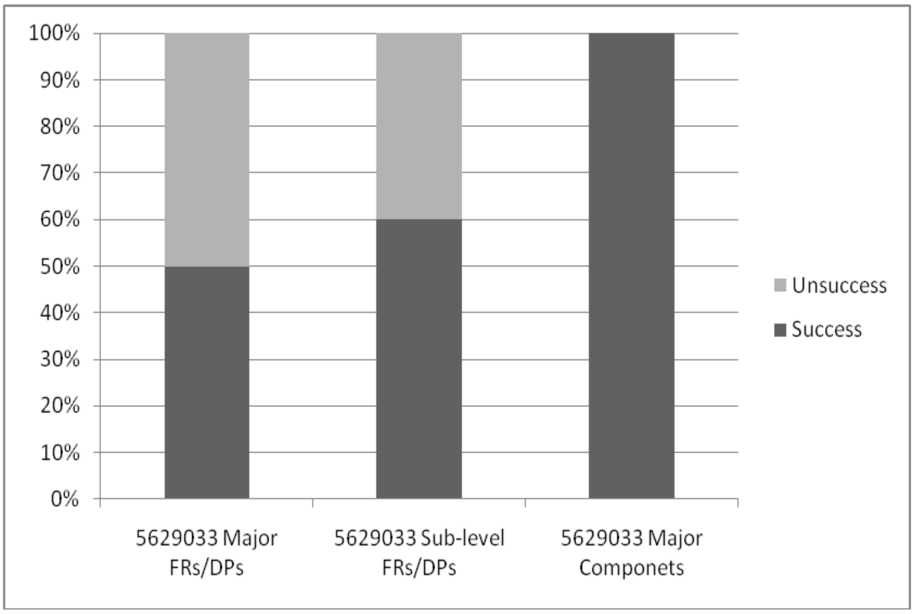

Fig. 6. Comparison between manual analysis and automatic analysis of U.S. Patent 5629033

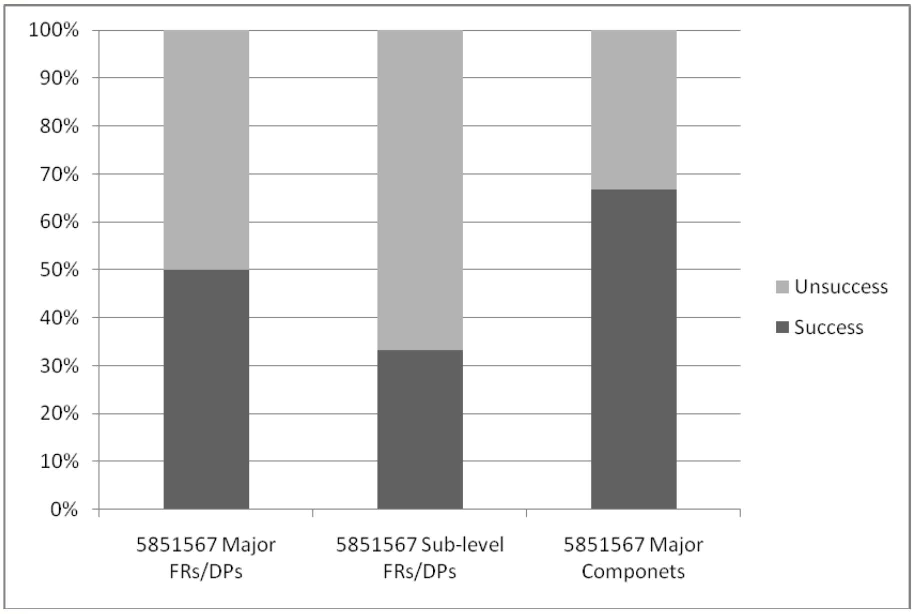

Fig. 7. Comparison between manual analysis and automatic analysis of U.S. Patent 5851567

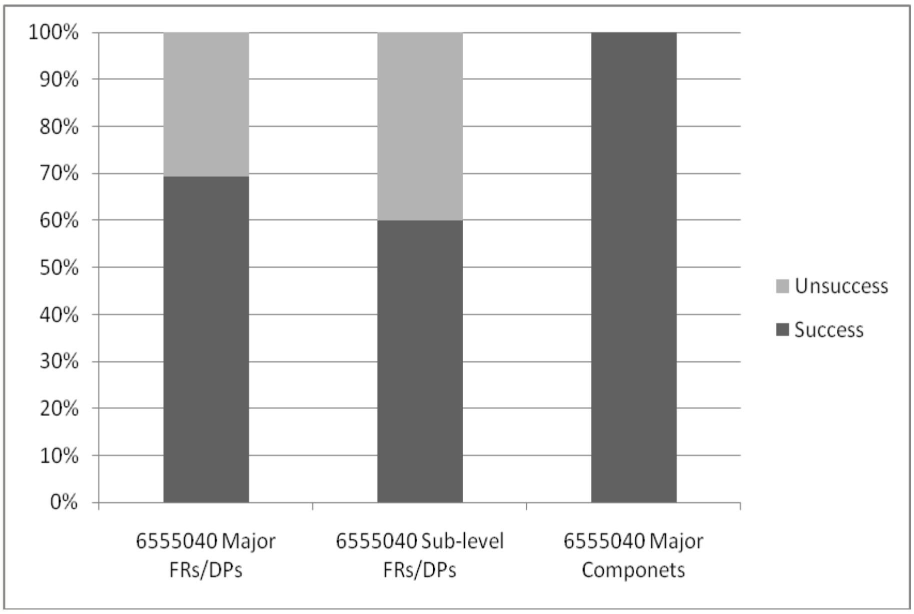

Fig. 8. Comparison between manual analysis and automatic analysis of U.S. Patent 6555040

4. Results and Discussion

The classification result and network performance may vary as the limited training sample is randomly divided into three parts for training, validation, and testing. However, this effect can be cancelled if a sufficient training sample is presented for training the network.

After the network is trained, test samples are applied to the network for classification. Table 9 indicates the automatic estimation of four patents. As all solutions in these four patents are apparent, the level of invention for test samples should be considered as 1. Therefore, this result shows that the estimation is reasonable.

By selecting FRs/DPs from patents ranked with level of invention, designers have sufficient knowledge regarding the scope of their designs. With the help of the framework of axiomatic design or TRIZ, more innovative solutions can be found cheaply and quickly.

Table 9. Level of invention estimation made by ANN

Patents No.	Level of invention estimation
6736626	1.36
5629033	1.47
5851567	1.28
6555040	1.19

Generating functional requirements and design parameter pairs from given patents has not been done previously because high quality text abstraction requires sophisticated natural language processing techniques that are still immature. Most of the work done in this area concentrates on extracting words instead of phrases or sentences to represent functions which can cause vagueness for readers. In this paper, the authors present the effort that has been done to show that this goal is feasible through using parsing and tagging techniques combined with axiomatic design theories.

Although the result indicates that the method adopted is still mechanical and inflexible, the result is still encouraging as most of statements of functional requirements and design parameters are highly readable and understandable compared with single words.

As this is a fresh attempt in this field, the method adopted is inevitably immature. For example, because both the parser and tagger used in this paper are statistically based, the training sample used will undoubtedly affect performance. Unfortunately, because there is no dedicated parser or tagger for patents, the accuracy may not be satisfactory in some cases. Also, the method proposed cannot be used so far for constructing functional requirements and design parameters in a hierarchical way, resulting in a loss of information.

The proposed evaluation of innovative potential is simple but effective. However, as the training sample used thus far is limited, the classification performance can be improved by preparing a larger sample in the future. Furthermore, the methodology for evaluating innovative potential in this paper depends on the number citations received which makes it less accurate for classifying patents that have received few citations. To reduce this dependency, the classification should be made based solely on the content of patent or design idea instead.

5. Conclusions and Future Work

In this paper, a framework for enhancing creativity by combining engineering design concepts, automatic function generation, and evaluation of innovativeness was proposed. By doing these steps, novel design concepts can be assessed and realized which facilitates innovation in engineering design activities. In this paper, the authors present the effort that has been done to generate functional requirements and design parameter pairs from given patents to show that this goal is feasible through using parsing and tagging techniques combined with engineering design theories. The result is still encouraging as most of statements of functional requirements and design parameters are highly readable and understandable compared with single words. The proposed evaluation of innovative potential is simple but effective for classifying patents that have already received citations.

In the light of the preliminary result, the authors will extend the work in the future by taking several steps. WordNet developed in Princeton University has been shown to be a useful tool in natural language processing. By combining this lexical database, phrases that have the same meaning can be grouped as one to make functional generation more accurate. Additionally, taking advantage of the axiomatic design framework to express functional requirements and design parameters in a hierarchy is another topic to be covered in future. In assessment of innovative potential, the authors will extend the application of NLP techniques to patents to create a training sample for a machine-learning model based on functions for classification instead of using the number of citations received or made. This step helps evaluate or predict the potential of an innovative work more independently. Also, this step will be helpful for entrepreneurs or inventors to evaluate their work even without citations. Finally, the authors intend to incorporate function generation and assessment of innovative potential into a standalone software suite.

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An Innovative Matrix-Based Approach for Designing Product Variety

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Abstract

New product development (NPD) and innovation are key factors that affect a company’s long-term survival and growth. The design process is an important stage in new product development (NPD). Based on graph theory and the weighting concept, this paper presents a Quantified Design Structure Matrix (QDSM) which is a systematic planning method of optimizing design priorities and product architecture for managing product variety from an informational structure perspective. Focusing on product variety and the design process in concurrent engineering (CE), the planning model is divided into two phases: global planning and local planning. The proposed method helps designers optimize the design planning and plan better design strategies for product variety. A case study is used to illustrate this method. The results verify that designers may concurrently create variant design solutions in a product family that can meet different market needs without extra effort being spent on redundant design loops.

Keywords: new product development (NPD), graph theory, concurrent engineering (CE), quantified design structure matrix (QDSM)

1. Introduction

Design for variety (DFV) is a design strategy and methodology that helps designers reduce the impact of variety on the life-cycle costs and time of a product (Martin and Ishii 1997). Various investigations have explored issues dealing with the strategic benefits of developing product platforms and the management of product families.

Suh (1990) viewed product variety as the proper selection of design parameters that satisfy variant functional requirements. Fujita and Ishii (1997) formulated the task structure of product variety design. Erens (1996) developed product variety under functional, technological, and physical domains. Martin and Ishii (1997) proposed Design for Variety (DFV), which is a series of methodologies with quantifying indices for reducing the influence of product variety on product life-cycle costs, and thus helping design teams develop decoupled product architectures. These studies have established a basis for product variety management.

Product variety is another orthogonal axis against the design process and product architecture and requires strategic design synthesis. Second, although all these studies provided some insight into the dependent relationships of a complex product for product variety design, they failed to expose and explore the logic behind these dependencies. Moreover, the operation process of the proposed tools is complex and inefficient. The tools are not easily applied to computational programming. Therefore, this paper focuses on optimizing product architecture by identifying the attributes of product components for design variety and on design priorities of product components for concurrent engineering (CE).

To deal with this problem, this paper proposes a structural matrix-based method called Quantified Design Structure Matrix (QDSM) based on the design structure matrix (DSM) (Steward 1981). For instance: (1) the traditional path searching method (Weinblatt 1972) adopted in the partitioning procedure is computationally inefficient; it is difficult to solve large design matrix. (2) Although many researchers (Kusiak and Wang 1993, Rogers 1989) have tried to improve the tearing algorithm, no optimal method exists for tearing. (3) The dependency strength between two product components cannot be really reflected using a binary matrix with “1 ”and “0 ”. The information is insufficient to dispose the coupled components for further analysis. Thus, this study attempts to solve these problems using the QDSM model.

QDSM can reduce complex system interactions into a logically oriented graph. This paper employs QDSM to establish a hierarchical component interaction structure, which can help designers determine component commonality, variety, and design priorities for design strategies. QDSM can help designers develop a product family. We expect that paper can provide a planning model for new product design and that the results can help designers concurrently create variant design solutions in a product family that can meet different market needs without extra effort being spent on redundant design loops.

2. Methodology: information structure analysis

2.1 Extended directed graph (EDG)

Once decomposed, the design process and product architecture can be described as a directed graph based on graph theory (Roberts 1976). The directed graph consists of a set of nodes, representing the design components, and a set of directed lines connecting these nodes. The directed lines or linkages reflect a dependency or a relationship between the connected components. Assume that $G = \langle V, E \rangle$ is a directed graph, where $V = \{v_1, v_2, ..., v_n\}$ is a set of nodes denoting *n* components, and $E = \{e_1, e_2, ..., e_n\}$ is a set of directed lines denoting the path and direction of information linkages. Each element of *E* corresponds to two nodes in *V*. However, there are some disadvantages to directed graphs. For instance: (1) Simple relationships. Most directed graphs can only describe sequential relationships. However, there are also parallel relationships and coupled relationships in the design process and product architecture. A directed graph cannot describe these relationships completely. (2) Scattered structure and difficulty to operate in computer language. Since directed graph models are described in a graphical and illogical way, it is not convenient to work with them on a computer. (3) The dependency strength between the product components cannot be described. This is a disadvantage when decomposing the design components, in particular, disposing coupled components for design priorities. (4) The hierarchical relationships of the design components cannot be clearly represented. An excellent plan and strategy for the design process and product architecture is thus difficult to make. (5) Furthermore, if information flows are complex or information content is great, the directed graph model will be messy.

Thus, we propose an extended directed graph (EDG) to present the original information model of a complex design process by quantifying the dependency strength between the product components. Furthermore, mapping EDG to DSM is proposed to describe a complex design process and product architecture. We are able to obtain an excellent plan for design priorities and product variety after analyzing the information flows hidden in DSM. In the next subsection, we introduce the basic theory of DSM.

2.2 Design structure matrix (DSM)

According to graph theory, the relationships between design components can be mapped to a matrix. The matrix is called a Design Structure Matrix (DSM) (Steward 1981), in which the rows and columns correspond to the design components. A DSM associated with a directed graph is a binary square matrix with m rows and columns, and n non-zero elements, where m is the number of nodes and n is the number of directed lines connecting these nodes in the directed graph. If there exists a directed line from node j to node i, then the value of element a_{ij} (column j, row i) is unity (or marked with an X). Otherwise, the value of the element is zero (or left empty). The DSM can be defined as follows:

Definition 1. Let *A* be a DSM with a $n \times n$ square matrix, where *n* denotes the number of components. The DSM is a binary Boolean matrix $A = [a_{ij}]_{n \times n}$. Its elements, a_{ij}, can only be “0” or “1”. Thus, it can be defined as:

$$a_{ij} = \begin{cases} 0 & (i = j \ \ or \ \ a_j \not\rightarrow a_i) \\ 1 & (a_j \rightarrow a_i) \end{cases} \tag{1}$$

In the matrix, the element $a_{ii} = 0$ is on the diagonal. “$a_j \rightarrow a_i$” denotes that component a_j input information to component a_i. Then, $a_{ij} = 1$, otherwise $a_{ij} = 0$. Figure 1 shows a classical DSM.

The matrix representation of a directed graph provides a systematic mapping among design components that is clear and easy to read regardless of size. It can be shown that an empty row represents a node without inputs, and that an empty column represents a node without outputs. Off-diagonal marks in a single row of the DSM represent all of the components whose output is required to perform the component corresponding to that row. Similarly, reading down a specific column reveals which components receive information from the component corresponding to that column. If one interprets the component ordering in the matrix as the execution sequence, then marks below the diagonal represent forward information transfer to later (i.e. downstream) components. This kind of mark is called a forward mark or a forward information link. Marks above the diagonal depict information fed back to earlier listed components (i.e. feedback mark or information link) and indicate that an upstream component depends on a downstream component. Figure 2 (Smith 1992) shows three configurations that characterize a system mapped from a directed graph to a DSM representation.

Backward

Feed forward

$$
\begin{array}{c|c}
 & \begin{matrix} a_1 & a_2 & \cdots & a_n \end{matrix} \\
\begin{matrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{matrix} & \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}
\end{array}
$$

Fig. 1. Design Structure Matrix.

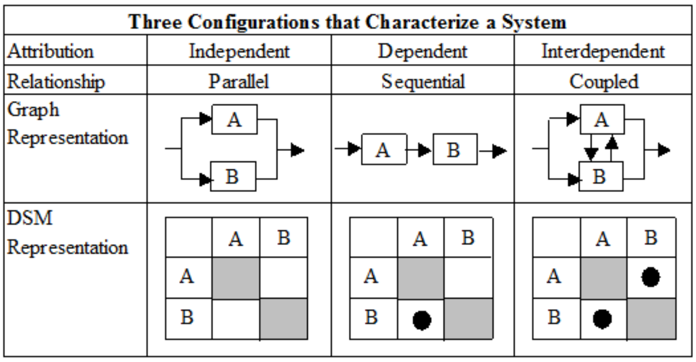

Fig. 2. Characterizing a system by DSM and directed graph representation.

2.3 Mapping from EDG to QDSM

There are many vague and uncertain relationships within design components when product configurations are considered. The traditional DSM cannot express fuzzy and uncertain interdependent relationships with "1" and "0". We utilize a simple weighting method to represent the complete dependency structure profile and dependency uncertainty of the design process and product architecture.

We not only use the directed lines to describe the relationship between the product components, but also quantify the dependency strength between product components in EDG. In order to assign weights to the relationships between design components, we apply a weighting scale with linguistics variables to define the degree of the dependency strength. After mapping EDG to DSM, the evaluation value a_{ij} of the dependency strength will be used instead of a "1" in DSM. The matrix will become a numerical DSM. It is called a quantified design structure matrix (QDSM).

Based on the weighting concept, we can employ linguistics variables to describe the degrees of the dependency strength within the product components. A variable is represented using a linguistic variable V, which is based on the linguistic scale: S_v = EL, VL, L, M, H, VH, EH where EL: Extremely Low (0); VL: Very Low (0.1); L: Low (0.3); M: Medium (0.5); H: High (0.7); VH: Very High (0.9); and EH: Extremely High (1). The element a_{ij} presents quantitatively the dependency strength between component a_i and component a_j and is defined as follows:

$$a_{ij} = \begin{cases} 0 & (i = j \quad or \quad a_j \rightarrow a_i) \\ K & (a_j \rightarrow a_i) \end{cases} \qquad (2)$$

where $K \in \{0,\ 0.1,\ 0.3,\ 0.5,\ 0.7,\ 0.9,\ 1\}$.The element a_{ij} is associated with a real number in the interval [0; 1]. To establish the universal weighting scale of linguistics variables, the linguistic variable set R_v is defined as:

$$R_v = \left\{ \frac{0}{extremely\ low}, \frac{0.1}{very\ low}, \frac{0.3}{low}, \frac{0.5}{medium}, \frac{0.7}{high}, \frac{0.9}{very\ high}, \frac{1}{extremely\ high} \right\} \qquad (3)$$

We can obtain an EDG by assigning weights to the relationships between each pair of components; the EDG can then be mapped to QDSM for further analysis. Figure 3 shows the mapping procedure from EDG to QDSM.

3. Re-engineering process based on QDSM

An important challenge of CE is making sound decisions at very early stages of product development where budgeted costs are low. All components in the downstream design should be considered at early stages, so that the potential problems can be found as early as possible.

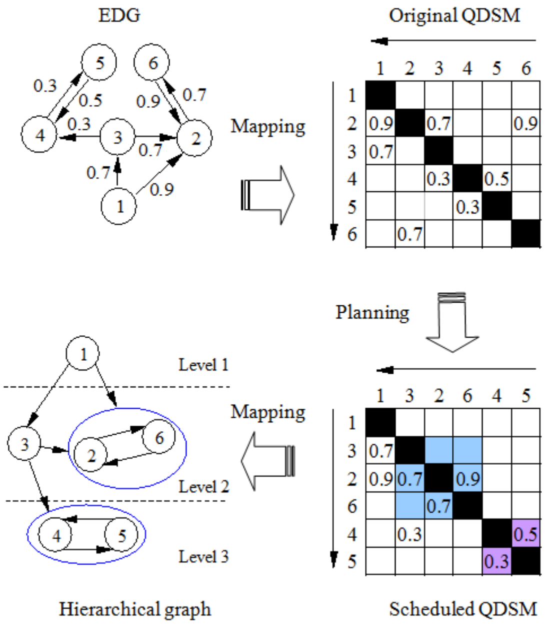

Fig. 3. Mapping from EDG to QDSM.

To achieve its aim, concurrent engineering uses the small local iterations to avoid the large scope iterations of the traditional sequential design process. From a microcosmic view, the early stages of concurrent engineering are focused on coupled phases which often arise from the small local iterations and can be expressed by the coupled relationship model. From a macroscopic view, the structure of the decoupled circuitry serves as an ideal model of the concurrent design process which emphasizes “do it right first”. If one interprets the component ordering in QDSM as the design sequence, the elements a_{ij} = 1 (i > j) below the diagonal represent the forward information transfer to later (i.e. downstream) components; and the elements a_{ij} = 1 (i < j) above the diagonal depict information fed back (or iteration) to earlier (i.e. upstream) components. Thus, the

QDSM of the ideal concurrent design process and optimal product architecture will become a lower triangular form. However, a complex design process and product architecture include many information loops in coupled mode that lead to iterations of product components, delaying the design period. The purpose of re-engineering is to reduce the iteration time as much as possible. Because the above QDSM is based on components, its re-engineering can be realized by the partitioning and tearing of QDSM. In the next subsection, we introduce the proposed planning method based on QDSM. The method includes two phases: global planning and local planning.

3.1 Global planning of the design process

QDSM can be considered as the transpose of the incidence matrix corresponding to EDG. The partitioning algorithm is adopted to identify the coupled components. The upper-diagonal marks of QDSM signify feedback and iterations of components. The purpose of partitioning is to transform QDSM into a lower triangular matrix in the global planning phase of the design process and product architecture. The Interpretative Structural Modeling (ISM) method (Warfield 1973, 1990) is adopted to realize and improve the partitioning algorithm of QDSM in the global planning phase. There are three main steps in the global planning phase: (1) sorting independent components, (2) identifying coupled components, and (3) arranging the ranks of the uncoupled components. We first introduce some definitions which will be used in the partitioning algorithm. The procedures of the partitioning algorithm are as follows:

Procedure 1. Sorting independent components.

The purpose of partitioning is to push forward the process of each component and recognize the coupled components in the design process. It is a gradually decreasing process. The gradually decreasing analysis of partitioning includes the sorting of independent components and also the recognition of coupled components. An independent component is defined in Definition 2.

Definition 2: In the fuzzy design structure matrix *A*, the components with a zero row-sum or a zero column-sum are called independent components. We take the condition $a_{ij} \in R$, if $\sum_{j=1}^{n} a_{ij} = 0$ or $\sum_{i=1}^{n} a_{ij} = 0$, and then we define the corresponding component of a_i, a_j as the independent component.

In this paper, we develop a simple and efficient procedure for finding a logical order of the components using the matrix form when no loops exist. The proposed algorithm starts by finding the input-degree of component *i*(*Ii*), which is the row sum of that component. Then, we rank the component with a zero row-sum, if it exists, to be the first component in the QDSM. This component with all its corresponding marks is deleted from the QDSM and the above process is repeated to find another component with a zero row-sum. If there are no components with a zero row-sum and the QDSM is not empty, then the design process contains cyclic flows of information and the procedure is terminated. Similarly, if we find a component with a zero column-sum, we can place it to the last position in the QDSM.

Procedure 2. Identify the coupled components.

The problem of identifying the coupled components set is translated into the problem of seeking strongly connected components in QDSM. Based on the algebraic technique of ISM, we can deduce a reachable matrix and a strongly connected matrix for identifying the coupled components from the incidence matrix of QDSM.

Definition 3 (Warfield 1990, Xiao 1997). Let *A* be the incidence matrix of QDSM and let *In* be the n-dimensional Boolean unity matrix; then, the transitive closure of $(A \cup I_n)^n$ is defined as the reachable matrix *P* of this QDSM.

The reachable matrix $P = (A \oplus I_n)^n = (p_{ij})_{n \times n}$ is deduced from incidence matrix *A* if a Boolean n-multiple product of $A \oplus I_n$ uniquely converges to *P* for all integers $n > n_0$, where n_0 is an appropriate positive integer, I_n is a n-dimensional Boolean unity matrix, and $\oplus$ is the logic Sum operator in Boolean sense (Warfield, 1990). Matrix P represents all direct and indirect linkages between components. Relationship transitivity is a basic assumption in ISM.

Definition 4 (Xiao 2001). Let Q be a strongly connected matrix. Matrix Q is the strongly connected judgment matrix of the reachable matrix P. Q is defined as follows:

$$Q = P \cap P^T = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & {}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \cap \begin{bmatrix} p_{11} & p_{21} & \cdots & p_{n1} \\ p_{12} & p_{22} & \cdots & p_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ p_{1n} & p_{2n} & \cdots & p_{nn} \end{bmatrix} = \begin{bmatrix} p^2{}_{11} & p_{12}\cdot p_{21} & \cdots & p_{1n}\cdot p_{n1} \\ p_{21}\cdot p_{12} & p^2{}_{22} & \cdots & p_{2n}\cdot p_{n2} \\ \cdots & \cdots & \ddots & \cdots \\ p_{n1}\cdot p_{1n} & p_{n2}\cdot p_{2n} & \cdots & p^2{}_{nn} \end{bmatrix}$$

(4)

where the matrix $P = (p_{ij})_{n\times n}$ is reachable, and P^T is the transpose of P. Matrix Q is denoted as

$$P \cap P^T = (p_{ij})_{n\times n} = (p_1, p_2, \cdots, p_n)^T \qquad (5)$$

where p_i is a n-dimensional row vector. Let the set composed by any of the unequal p_i be $\{p_1', p_2', \cdots, p_m'\}$ $(1 \le m \le n)$, Then:

(1) The number of coupled components in QDSM is $m'(m' \le m)$, where m' is the total number of row vectors that have at least one component whose value is equal to 1 in $\{p_1', p_2', \cdots, p_m'\}$.

(2) If p_i' is the row vector that has at least one component whose value is equal to 1 and all the components whose value is equal to 1 are $p_{ik1}, p_{ik2}, \cdots, p_{ikp}, (2 \le p \le n)$, then C = $\{C_{ik1}, C_{ik2}, \cdots, C_{ikp}\}$ is a coupled components set.

If the path is reachable from component i to component j, then $p_{ij} = 1$. If the path is reachable from component j to component i, then $p_{ji} = 1$. Thus, component i and component j are reachable from each other, if and only if $p_{ij} \cdot p_{ji} = 1$. In matrix Q; if the non-zero elements of the ith row are in the j1th, j2th…, $j$kth columns, then, component i, component $j1$, component $j2$,…, component jk form a strongly connected component. The components corresponding to these components are in a coupled set.

Procedure 3. Arrange the ranks of the uncoupled components.

Definition 5 (Cui *et al.* 1997). The reachable matrix P becomes a reduced matrix P', if every coupled component set is merged into one component, and the rows and columns corresponding to the coupled component set have been merged into one row and column.

Definition 6 (Xiao 1997). Let $P' = (p_{ij}')_{m\times m}$ be the reductive matrix of a QDSM. $P'E_{l-1} = (p_1, p_2, \cdots, p_m)^T$, where $l \ge 1$, $1 \le m \le n$, the m-dimension vector $E_0 = (1,1,\cdots,1)^T$, $E_l = (e_1, e_2, \cdots, e_m)^T$, where

$$e_i = \begin{cases} 0, & p_i \in \{0,\ 1\}; \\ 1, & p_i \notin \{0,\ 1\}; \end{cases} \quad (i = 1,\ 2,\ \cdots, m). \quad (6)$$

Then, for component C_i, $p_i = 1$ is the necessary and sufficient condition of $L_l = \{C_i\}$,where L_l means that the level of component C_i is l in QDSM.

Definition 6 can be easily realized on a computer to arrange the level of coupled components sets. According to the above method, the partitioned QDSM of the design flow can be easily obtained. The execution of design components becomes sequential. The rank of the design components indicates the priority level of all the components. The design process is in a lower triangular form, and there are no large-scale or whole iterations.

3.2 Local planning of the design process

Creating a lower triangular form by partitioning avoids large-scale iterations, but loops in coupled blocks still exist. It is thus necessary to break apart these loops and plan them. To reduce the feedback and iterations caused by coupled information flow, we use a removing coupling method called tearing to make certain the original iteration sequence of coupled components by analyzing the relationships between components. The basic principle of the tearing algorithm is to cut off the loops at the weakest point and to design the components with the least information-dependent intensity. Here, we propose a simple and efficient method to eliminate the coupled component sets.

No optimal method exists for tearing, but many researchers (Kusiak and Wang 1993, Rogers 1989) have identified two important criteria for tearing procedures.

(1) Minimal number of tears: the motivation behind this criterion is that tears represent an approximation or an initial guess to be used; we should reduce the number of these guesses.

(2) Confine tears to the smallest blocks along the diagonal: the motivation behind this criterion is that if there are to be iterations within iterations (i.e. blocks within blocks), these inner iterations are performed more often. Therefore, it is desirable to confine the inner iterations to a small number of components.

In this paper, we propose a simple and efficient method to decouple the coupled components sets. We now look at tearing each block separately. For each block in the partitioned QDSM, the block information input-degrees (*IIi*) and the block information output-degrees (*IOi*) are calculated for all the components within that block. Note that *IIi* and *IOi* are the row and column sums of component *i*, respectively; however, only the subset of components and marks contained within the block is considered. Next, we calculate the ratio *Ri* = *IIi*/*IOi*, which is a relative importance index. Another issue to consider is the relative importance of input and output information. In a QDSM, the elements above the diagonal denote the iteration of design information. The feedback information of more downstream components will cause more large-scale iterations. We want to have the least amount of feedback information during the design process in concurrent design. In order to identify the weights for the element $E_{ij}(i < j \le n)$ above the diagonal, we can adopt the related distance from E_{ij} to the corresponding element E_{ii} on the diagonal to denote the relative importance. The weight of the element $E_{ij}(i < j \le n)$ above the diagonal can be defined as $W_a = |j-i|$. For element $E_{ij}(j < i \le n)$ below the diagonal, we define its weight as $W_b = 1$. Both *IIi* and *IOi* can be defined as follows:

$$II_i = \sum_{j=1}^{i-1} C_{ij} \cdot W_b + \sum_{j=i+1}^{n} C_{ij} \cdot W_j \qquad (i, j \le n) \qquad (7)$$

$$IO_i = \sum_{i=1}^{i-1} C_{ij} \cdot W_i + \sum_{i=j+1}^{n} C_{ij} \cdot W_b \qquad (i, j \le n) \qquad (8)$$

where, *n* denotes the number of coupled components, and W_i and W_j are the weights corresponding to the elements. The steps of the tearing procedure are listed as below:

(1) Calculate the *IIi* and *IOi* of component *i* , where *i* = 1 to *n*.

(2) Calculate the ratio *Ri* = *IIi*/*IOi*.

(3) Compare each *Ri* corresponding to component *i*. Component *i* with the minimum *Ri* value is scheduled first within the block, since it requires minimum input and delivers maximum output.

(4) After choosing the top-priority component, the scheduled component and all its corresponding marks are removed from the block. Next, we check if the loop was broken by the removal of the scheduled component using the above procedure. If an information loop is encountered again within the block, the process of finding new *Ri* values is repeated. After ranking all the components within a block, we tear all the feedback marks in the block.

4. A case study

4.1 Object product

This study employs the variant design of a PLC (Power Line Communication) product to illustrate the proposed methodology. This case study involves a Taiwanese electronic appliances manufacturer (Company A). Ninety percent of the products of this company are Original Design Manufactured (ODM), and are mainly exported to America, Europe and Japan. Based on their experiences and manufacturing technologies, Company A aims to develop a series of products to simultaneously meet the requirements of each segmented market, and to provide variety in mass customization.

4.2 Identify market-driven variety

At present, the position of the PLC products of Company A belongs to cost driven market segmentation with unrefined style and low-tech. Company A hopes that their PLC product can be developed toward high-value market segmentation with high-style and high-tech in the future (Figure 4). In this case study, market planning is performed by the product development team, which includes the marketing, planning, and design departments of Company A. The market planning is aimed at two different markets (technology variety) with two different appearances (style variety), so four products need to be concurrently developed.

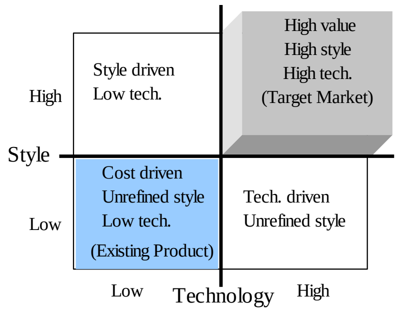

Fig. 4. Market segmentation and position map of PLC Product.

Finally, the design team identifies the initial product specifications (Table 1) for concurrently developing four variant PLC products for the different segmented markets.

Product Spec.	Product 1	Product 2	Product 3	Product 4
Main Function	200 Mega PLC	85 Mega PLC	55 Mega PLC	55 Mega PLC
Extensional Functions	Audio, Video, VoIP	Audio, Video	X	X
Security device	Electronic Key	X	Electronic Key	X

Table 1. Initial PLC product specifications.

Based on the existing PLC product of Company A and the initial product specifications, the design team identifies all required physical components, as shown in Table 2.

Table 2. Components list for PLC product.

1. Key PCBA	9. Functional Base Cover
2. Functional PCBA	10. Power Plug
3. Main System PCBA	11. Power Button
4. Key Front Cover	12. Key Button
5. Key Back Cover	13. Led Lens
6. Main Top Cover	14. Main IO Plate
7. Main Base Cover	15. Functional UI Plate
8. Functional Top Cover	

4.3 Build QDSM for PLC product

Next, we represent the interdependent relationships of 15 product components from an EDG mapping to a 15 x 15 square QDSM using the proposed weighting method (Equation 3) which assigns weights to the dependency strength between each pair of product components. This numerical DSM becomes a QDSM (Figure 5).

Part Name	No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Key PCBA	1					0.3							0.2			
Functional PCBA	2									0.3						
Main System PCBA	3							0.5				0.2		0.2		
Key Front Cover	4	0.5		0.5		0.5					0.6		0.3			
Key Back Cover	5	0.5			0.3											
Main Top Cover	6			0.8				0.4				0.3		0.2		
Main Base Cover	7			0.9			0.6									
Functional Top Cover	8		0.6	0.8						0.2						
Functional Base Cover	9		0.5						0.6							0.4
Power Plug	10			0.9			0.5									
Power Button	11			0.8			0.7									
Key Button	12	0.8			0.9											
Led Lens	13			0.9			0.8									
Main IO Plate	14			0.4				0.3								
Functional UI Plate	15		0.8												0.7	

Fig. 5. Original QDSM for PLC product components.

4.4 Global planning

4.4.1 Identifying coupled components sets

The original QDSM can be clustered and reordered using the improved partitioning algorithm illustrated in section 3.1. The incidence matrix, reachable matrix, and strongly connected matrix can be deduced. First, we can transform the original QDSM into a binary Boolean matrix. The matrix is called incidence matrix A and is shown below.

$$A=\begin{bmatrix}
0&0&0&0&1&0&0&0&0&0&0&1&0&0&0\\
0&0&0&0&0&0&0&0&1&0&0&0&0&0&0\\
0&0&0&0&0&0&1&0&0&0&1&0&1&0&0\\
1&0&1&0&1&0&0&0&0&1&0&1&0&0&0\\
1&0&0&1&0&0&0&0&0&0&0&0&0&0&0\\
0&0&1&0&0&0&1&0&0&0&1&0&1&0&0\\
0&0&1&0&0&1&0&0&0&0&0&0&0&0&0\\
0&1&1&0&0&0&0&0&1&0&0&0&0&0&0\\
0&1&0&0&0&0&0&1&0&0&0&0&0&0&1\\
0&0&1&0&0&1&0&0&0&0&0&0&0&0&0\\
0&0&1&0&0&1&0&0&0&0&0&0&0&0&0\\
1&0&0&1&0&0&0&0&0&0&0&0&0&0&0\\
0&0&1&0&0&1&0&0&0&0&0&0&0&0&0\\
0&0&1&0&0&0&1&0&0&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&0&0&0&0&1&0
\end{bmatrix}$$

Second, according to Definition 3, the reachable matrix P can be obtained as below.

$$P=\begin{bmatrix}1&0&1&1&1&1&1&0&0&1&1&1&1&0&0\\0&1&1&0&0&1&1&1&1&0&1&0&1&1&1\\0&0&1&0&0&1&1&0&0&0&1&0&1&0&0\\1&0&1&1&1&1&1&0&0&1&1&1&1&0&0\\1&0&1&1&1&1&1&0&0&1&1&1&1&0&0\\0&0&1&0&0&1&1&0&0&0&1&0&1&0&0\\0&0&1&0&0&1&1&0&0&0&1&0&1&0&0\\0&1&1&0&0&1&1&1&1&0&1&0&1&1&1\\0&1&1&0&0&1&1&1&1&0&1&0&1&1&1\\0&0&1&0&0&1&1&0&0&1&1&0&1&0&0\\0&0&1&0&0&1&1&0&0&0&1&0&1&0&0\\1&0&1&1&1&1&1&0&0&1&1&1&1&0&0\\0&0&1&0&0&1&1&0&0&0&1&0&1&0&0\\0&0&1&0&0&1&1&0&0&0&1&0&1&1&0\\0&1&1&0&0&1&1&1&1&0&1&0&1&1&1\end{bmatrix}$$

Third, according to Definition 4, the strongly connected matrix Q can be deduced as follows:

$$Q=P\cap P^{T}=\begin{bmatrix}1&&&1&1&&&&&&&1&&&\\&1&&&&&&1&1&&&&&&1\\&&1&&&1&1&&&&1&&1&&\\1&&&1&1&&&&&&&1&&&\\1&&&1&1&&&&&&&1&&&\\&&1&&&1&1&&&&1&&1&&\\&&1&&&1&1&&&&1&&1&&\\&1&&&&&&1&1&&&&&&1\\&1&&&&&&1&1&&&&&&1\\&&&&&&&&&1&&&&&\\&&1&&&1&1&&&&1&&1&&\\1&&&1&1&&&&&&&1&&&\\&&1&&&1&1&&&&1&&1&&\\&&&&&&&&&&&&&1&\\&1&&&&&&1&1&&&&&&1\end{bmatrix}$$

From matrix Q, we can find that the strongly connected components include $\{C_1,C_4,C_5,C_{12}\}$, $\{C_2,C_8,C_9,C_{15}\}$, $\{C_3,C_6,C_7,C_{11},C_{13}\}$, $\{C_{10}\}$, and $\{C_{14}\}$. The coupled components sets are $\{C_1,C_4,C_5,C_{12}\}$, $\{C_2,C_8,C_9,C_{15}\}$, and $\{C_3,C_6,C_7,C_{11},C_{13}\}$.

According to Definition 5, the reduced matrix P' of the reachable matrix P is:

$$P'=\begin{array}{c}\begin{matrix}s_1&s_2&s_3&s_4&s_5\end{matrix}\\\begin{bmatrix}1&&1&1&\\&1&1&&1\\&&1&&\\&&1&1&\\&&1&&1\end{bmatrix}\end{array}$$

where s_1 denotes coupled set $\{C_{1,4,5,12}\}$, s_2 denotes coupled set $\{C_{2,8,9,15}\}$, s_3 denotes coupled set $\{C_{3,6,7,11,13}\}$, s_4 denotes $\{C_{10}\}$, and s_5 denotes $\{C_{14}\}$. Based on the Definition 6, the order levels of all product components can be deduced as:

$E_0=(1,\ 1,\ 1,\ 1,\ 1)^T$, $P'E_0=(3,\ 3,\ 1,\ 2\ ,2)^T$, $L_1=\{C_{3,6,7,11,13}\}$.

$E_1=(1,\ 1,\ 0,\ 1,\ 1)^T$, $P'E_1=(2,\ 2,\ 0,\ 1,\ ,1)^T$, $L_2=\{C_{10},\ C_{14}\}$.

$E_2=(1,\ 1,\ 0,\ 0,\ 0)^T$, $P'E_2=(1,\ 1,\ 0,\ 0,\ 0)^T$, $L_3=\{C_{1,4,5,12},\ C_{2,8,9,15}\}$

According to the above order levels of product components, the re-engineered QDSM can be obtained as shown in Figure 6.

Level	Part Name	No.	3	6	7	11	13	10	14	1	4	5	12	2	8	9	15
1	Main System PCBA	3	■		0.5	0.2	0.2										
1	Main Top Cover	6	0.8	■	0.4	0.3	0.2										
1	Main Base Cover	7	0.9	0.6	■												
1	Power Button	11	0.8	0.7		■											
1	Led Lens	13	0.9	0.8			■										
2	Power Plug	10	0.9	0.5				■									
2	Main IO Plate	14	0.4		0.3				■								
3	Key PCBA	1								■		0.3	0.2				
3	Key Front Cover	4	0.5					0.6		0.5	■	0.5	0.3				
3	Key Back Cover	5								0.5	0.3	■					
3	Key Button	12								0.8	0.9		■				
3	Functional PCBA	2												■		0.3	
3	Functional Top Cover	8	0.8											0.6	■	0.2	
3	Functional Base Cover	9												0.5	0.6	■	0.4
3	Functional UI Plate	15							0.7					0.8			■

Fig. 6. A partitioned QDSM for PLC product components.

4.5 Local planning

We next decouple the coupled components sets. We take coupled block 1 as an example. According to section 3.2, we can calculate the ratio index *Ri* = *IIi*/*IOi* as shown in Table 3.

Table 3. The calculation of the tearing procedure.

Activity i	*II i*	*IO i*	*R i*	*Rank*
C_3	2.4	3.4	0.71	1
C_6	2.4	2.1	1.14	3
C_7	1.5	1.4	1.07	2
C_{11}	1.5	1.2	1.25	5
C_{13}	1.7	1.4	1.21	4

From the above analysis, we can obtain the new order of the product components of the coupled set from [*C3, C6, C7, C11, C13*] to [$C_3 \Rightarrow C_7 \Rightarrow C_6 \Rightarrow C_{13} \Rightarrow C_{11}$]. The other coupled sets can be decoupled in the same manner. After the tearing procedure, we can obtain the final component sequence in a QDSM (Figure 7); it can be mapped to a hierarchical graph automatically. Figure7 shows the interaction matrix after an appropriate rearrangement of the order. Three chunks form in the PLC product, namely C1: Main module, C2: Key module, and C3: Functional Module. The precedence of the three chunks is determined by the inter-chunk interactions. Based on concurrent engineering, we can assign these three modules to three designers, respectively, to reduce the product development time. Finally, according to the hierarchical graph, we can figure out the optimal design process and product architecture for PLC product development.

The identified relationships represent design constraints and incidence between product components that cope with the design knowledge of the specific product. The bottom row in Figure 7 shows the S value (sum of rows), indicating the degree to which each component influences others and the third-last column lists the R value (sum of columns), indicating the degree to which each component is influenced by the others. The last two columns of Figure 7 list the values of (S + R) and (S –R), respectively. The (S + R) value indicates the sum of interactions of a component, including the ‘supplying’ and ‘requiring’ interactions. The (S – R) indicates the difference between the influencing and influenced interactions of a component; a higher value indicates that the component is dominant. For example,

Figure 7 shows that the highest (S + R) value is 6.9 for component 3, namely the Main System PCBA. The two highest (S – R) values are 1.6 and 5.1 for component 2 and component 3, respectively, namely the Functional PCBA and Main System PCBA. Figure 8 shows the (S – R) plotted against (S + R). This graph is an overall indicator of how interactive/dominant a component is. For example, a high (S – R) value indicates that changes to the component have a relatively high propagation strength. A high (S + R) value indicates an interface component; changes to which affect or refer to numerous components.

Chunk	Module	Level	Component	No.	3	7	6	13	11	10	14	1	5	4	12	2	8	9	15	*R-value*	*S+R*	*S-R*
C1	Main Module	1	Main System PCBA	3		0.5		0.2	0.2											0.9	*6.9*	*5.1*
		1	Main Base Cover	7	0.9		0.6			Chunk 1										1.5	*2.7*	*-0.3*
		1	Main Top Cover	6	0.8	0.4		0.2	0.3											1.7	*4.3*	*0.9*
		1	Led Lens	13	0.9		0.8													1.7	*2.1*	*-1.3*
		1	Power Button	11	0.8		0.7													1.5	*2*	*-1*
		2	Power Plug	10	0.9		0.5								Chunk 2					1.4	*2*	*-0.8*
		2	Main IO Plate	14	0.4	0.3														0.7	*1.4*	*0*
C2	Key Module	3	Key PCBA	1									0.3		0.2					0.5	*2.3*	*1.3*
		3	Key Back Cover	5								0.5		0.3						0.8	*1.6*	*0*
		3	Key Front Cover	4	0.5					0.6		0.5	0.5		0.3					2.4	*3.6*	*-1.2*
		3	Key Button	12								0.8		0.9						1.7	*2.2*	*-1.2*
C3	Functional Module	3	Functional PCBA	2														0.3		0.3	*2.2*	*1.6*
		3	Functional Top Cover	8	0.8											0.6		0.2		1.6	*2.2*	*-1*
		3	Functional Base Cover	9										Chunk 3		0.5	0.6		0.4	1.5	*2*	*-1*
		3	Functional UI Plate	15							0.7					0.8				1.5	*1.9*	*-1.1*
			S-value		6	1.2	2.6	0.4	0.5	0.6	0.7	1.8	0.8	1.2	0.5	1.9	0.6	0.5	0.4			

Fig. 7. A re-engineered QDSM for PLC product design.

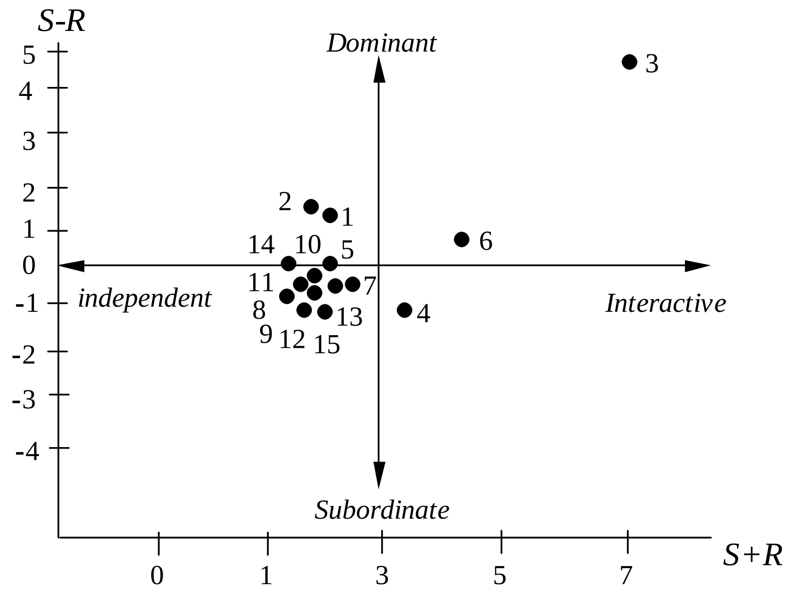

Fig. 8. Plotted diagram of component interaction.

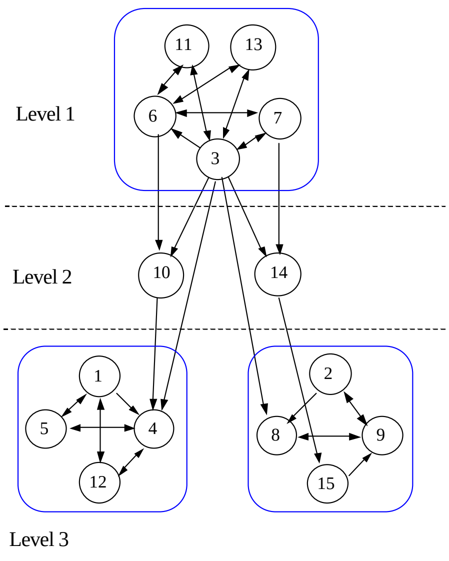

Fig. 9. Hierarchical graph of component interaction.

Figure 9 shows the hierarchical graph of the design constraint flow derived from the re-engineered QDSM. In this graph, the circles represent components, the oriented lines are design constraints provided by the source components, and the rounded rectangles indicate a set of mutually interactive components, which are integrated as a module. These modules and other components then are further grouped into chunks according to the frequency of their interactions.

4.6 Identifying the attributes of product components for design strategies

It is very important to develop a series of products with different depth and width dimensions for design variety. We need to identify the attribute of each component for the variant design and cost down (Halman et al, 2003). For example, we must define which component can be developed to be a platform, a module, or a standardized part for commonality in our product family. In general terms, the goal of the design team is to design the product platform architecture so that as much of the design as possible is standardized across generations and across the product family (Jose and Tollenaere, 2004). The design team tries to modularize parts of the design that cannot be standardized. Definitions of these terms are listed below.

(1) *Modularized*: this is a grouping concept for product design. Components are designed as building blocks which can be grouped together to form a variety of products (Salvador et al., 2002**)**. This concept promotes standardization and the re-use of existing modules to develop a product family. There are some interdependent relationships between these modularized components. This implies that these components have strongly connected relationships and they will become a functional modular design. We can identify the modularized parts using global planning analysis.

(2) *Standardized*: it is expected that the components will not change across generations and across the product family. These standardized parts will become commonality parts within the product family. This implies that a product can meet all the market requirements without having to be redesigned (Ulrich and Eppinger 2000). These components have higher independence. We can identify these standardized parts by their position in the independent- dominant or independent- subordinate quadrant in Figure 8.

(3) *Platform*: this is a design architecture concept of compromising interface definitions and key-components. It helps the design team make decisions on how to rearrange the mapping between the physical components and functions, and how to define interfaces. This implies that the platform is the main technological base for deriving different product families (Du et al., 2001). These components have higher dominance. We can identify these platform parts by their position in the interactive-dominant or independent -dominant in Figure 8.

(4) *Variety*: this is the most popular attribute for product components, especially in identifying appearance parts (Dahmus et al., 2000). We can identify these variety parts by position in the independent-subordinate or interactive-subordinate quadrant in Figure 8.

Besides the above the criteria, we must synthetically consider the other factors including appearance parts and structural parts, for identifying the attribute of each component. If a product design has better configurations using modularized, standardized, and platform parts, the development costs including mold costs and parts costs will be reduced. The main cost reduction criterion is to use as many standardized and modularized parts as possible across the product family.

From the above analysis, we only establish the optimal design process for CE and determine the attributes of product components for designing a product family. According to the segmented market requirements and the analysis results of QDSM, we can illustrate the different requirements of components and define the attribute of each component for concurrently developing four variant PLC products. Figure10 shows the individually required components for four variant PLC products in hierarchy graph. Finally, based on design variety and cost reduction criteria, we define all attributes of product components in Figure 11.

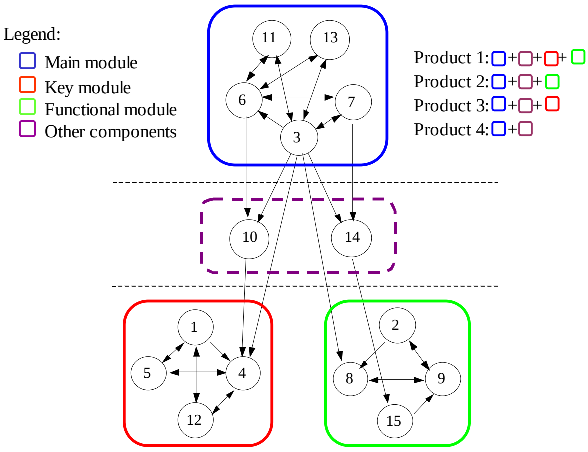

Fig. 10. Individual requirements of components for four variant PLC products.

4.7 Developing a product family

According to the above analysis and design strategies, the designers of company A create four variant products to meet two different market needs and design objective. The product proposals are shown in Figure 12.

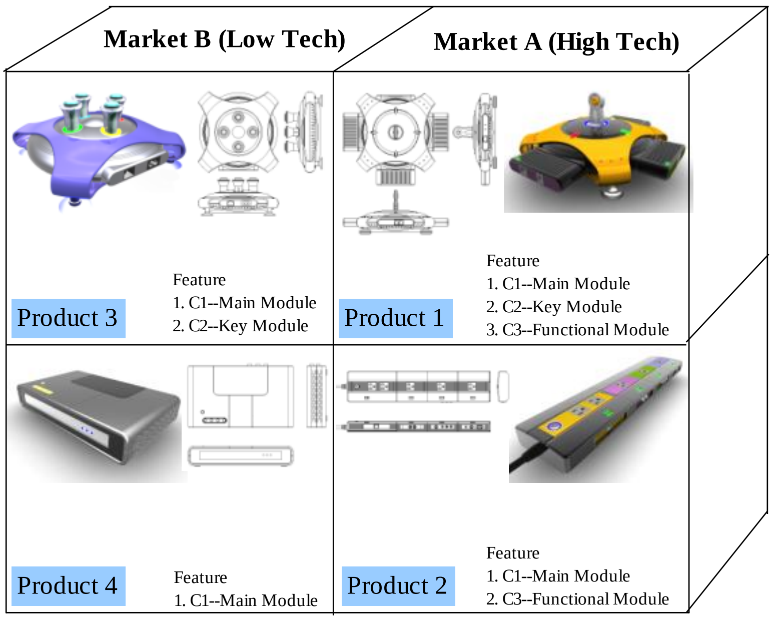

Fig.12. The product proposals for four variant PLC products.

Chunk	Module	Component	No.	Attribute	Product 1	Product 2	Product 3	Product 4
C1	Main Module	Main System PCBA	3	Platformization	V	V	V	V
		Main Base Cover	7	Variety	V	V	V	V
		Main Top Cover	6	Variety	V	V	V	V
		Led Lens	13	Variety	V	V	V	V
		Power Button	11	Variety	V	V	V	V
		Power Plug	10	Standardization	V	V	V	V
		Main IO Plate	14	Standardization	V	V	V	V
C2	Key Module	Key PCBA	1	Platformization	V		V	
		Key Back Cover	5	Variety	V		V	
		Key Front Cover	4	Variety	V		V	
		Key Button	12	Variety	V		V	
C3	Functional Module	Functional PCBA	2	Platformization	V	V		
		Functional Top Cover	8	Variety	V	V		
		Functional Base Cover	9	Variety	V	V		
		Functional UI Plate	15	Standardization	V	V		

Fig. 11. The attribute of each component of the PLC products

5. Conclusions

This research proposed a new system approach for design configurations that considers the optimal design process and product architecture for product variety based on an existing product. QDSM is a compact representation of the information structure of the design process and product architecture. It is a design configuration method that shows the order in which the design components are performed, and what components need to be verified. Our proposal is an enhanced structural model which can be used to visualize the hierarchical structure of product components and optimize the design process for CE. The proposed methodology is divided into two phases: global planning and local planning. The global planning phase focuses on identifying the coupled components sets and rearranges the uncoupled sets using an improved partitioning algorithm. In the local planning phase, a new tearing algorithm is proposed to decouple the coupled components for an optimal design sequence. The procedures of global planning and local planning are presented to re-engineer a design process and product architecture. The proposed approach helps designers and managers optimize the design configurations and plan better design strategies for designing a product family. A case study in PLC product family design was conducted to demonstrate the feasibility and effectiveness of the proposed design configuration approach.

Characteristics of the proposed approach are summarized as follows:
(1) By applying the fuzzy linguistic variables to quantify the degree of dependency between product components, EDG can be carried out and mapped to the proposed QDSM model for further analysis.
(2) By modeling the global planning method, including the reachable matrix, strongly connected matrix, and hierarchical analysis based on the Boolean algebraic operation, the strongly connected components and hierarchical level of product components can be determined. It is a computable method for grouping strongly connected components and a visual hierarchical structure of product components.
(3) By modeling the local planning method, including the calculations of the information input-degrees (IIi), the information output-degrees (IOi), and the ratio $Ri = IIi/IOi$, the optimized design priorities and product architecture for design strategies can also be determined.
(4) By identifying the attributes of product components including modularization, platformization, standardization, and variety based on the analysis results of QDSM, better design strategies for concurrently product family design can be obtained.

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