Intelligent Adaptive and Self-Adaptive Product Platform Design for Mass-Customization

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ABSTRACT

Many current mass-customization strategies are built from traditional design-by-compromise strategies that have too often shifted trade-offs from one place to another, such that mass-customization has been achieved at the expense of something else. The paper discusses inventive strategies and trends of evolution uncovered during a 2000 person year study of the innovation process and how these can be used to help generate the breakthrough paradigm shifts that will enable mass-customization to be achieved without compromising other design factors. Key to these evolutionary shifts are seen to be the resolution of conflicts and contradictions in which different customers require distinctly different amounts of a given parameter (for example; a colour should be 'red and blue', or size should be 'big and small'). The paper demonstrates how the evolution to adaptive and intelligently self-adapting systems offers enormous scope for achieving precisely these sort of contradiction-breaking design solutions. The paper contains several emerging examples of such intelligent adaptation being used in the mass-customization context.

Introduction

In their attempts to conduct business more effectively, the large majority of organisations adopt innovation strategies built on trade-off and compromise, in which one aspect of business performance is improved at the expense of another. A systematic programme of research to identify and distill the best practices has shown that those organisations that sought to challenge and eliminate the compromises and contradictions that their contemporaries assumed were unchallengeable or fundamental, have achieved considerably better business performance (Reference 1). Building on a preceding study which probably represents the biggest study of creativity ever conducted, the paper examines and describes some of the dynamics of system evolution uncovered following the analysis of successful solutions from across all fields of human endeavour.

Among the key findings uncovered during the research is the fact that successful innovations evolve in a direction of increasing ideality. Ideality is defined as the functional benefits (or, more accurately, the customer *perceived* benefits) delivered by a system, divided by the sum of the cost of producing the system plus the harmful side effects that it produces. The methodology subsequently built around this directionality of innovation then speculated that if there was a general direction of evolution, there ought to also be a destination – an evolutionary end-point. This end-point was given the title ‘ideal final result’ (IFR). Based on the ideality definition, the ideal final result for any given system occurs when the functional benefit desired by the customer is achieved with zero cost and zero harm. In other words, the ideal final result system delivers the useful functions, without the need for the system. Although in many senses this end-point is best viewed as a hypothetical destination for the evolution of a system (there are nevertheless many systems that have achieved such an ideal final result state – Reference 2), the concept is beginning to have a significant influence on the innovation strategy within several organisations.

The purpose of this paper is to examine the IFR concept in more detail, and specifically to examine what happens when customer and supplier effects are taken into account. In terms of customer effects, the central issue becomes the fact that every single customer of a product or service potentially has a different definition of his or her IFR. In terms of the supplier, the conflict between what the customer wants and what the supplier is prepared to offer is viewed as the key issue. The differences between customer IFR definitions and supplier IFR definitions are illustrated schematically in Figure 1.

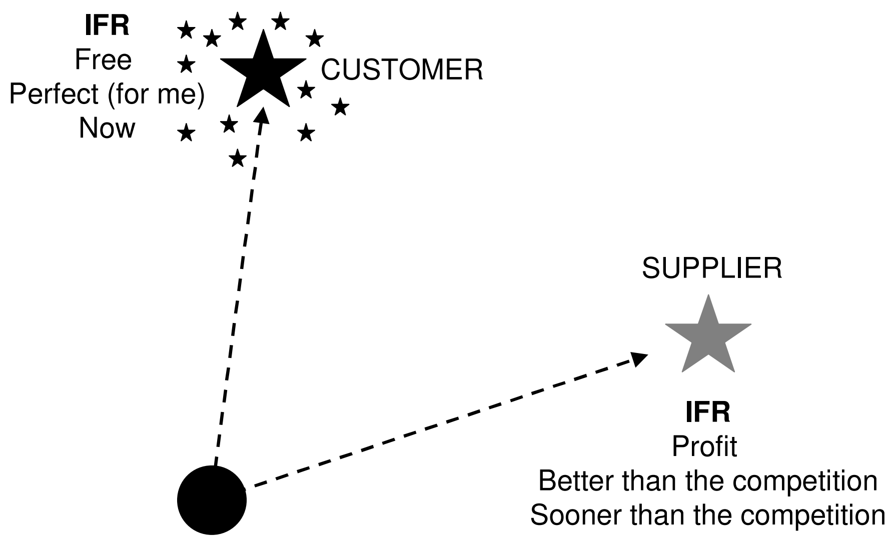

Figure 1: Different IFR Perspectives

The figure suggests that in terms of the customer, with some minor variation (illustrated by the array of different star shapes), customer ideality tends towards systems that are free, perfect for the requirements of an individual (which may in turn vary with time, or even time of day), and delivered now. The supplier on the other hand is in the business of delivering value to shareholders and staying in business – an ideal final result direction that is often considerably different to what the customer wants. To take a trivial example, the manufacturers of lawnmowers are traditionally in the business of delivering machines that are quieter, more efficient, more aesthetically pleasing, and more reliable (as long as the warranty is still running) than the designs of their competitors. The customer on the other hand – or rather the majority; for some people the idea of mowing their lawn is their definition of an ideal Sunday afternoon – is much more likely to have an ideal final result of a lawn that requires no maintenance. In other words, they don't want a lawnmower at all.

Possible arguments over whether the IFR definitions are 'right' are deemed irrelevant in the context of this paper. What is highly relevant, however, are the ideas hinted at above, in which different customers have different definitions of what they want from a product or service, and in which suppliers face the challenge of trying to deliver these expectations (if they don't; someone else probably will) while still maintaining a profitable business.

The differences between what different customers want from a product or service are central to the ‘customization’ part of mass-customization. The conflict between what the customer wants and what the supplier is affordably able to give is central to the ‘mass’ part.

What the systematic innovation research has subsequently gone one to demonstrate is that one of the fundamental aspects of evolution is the successive emergence and resolution of conflicts and contradictions between different attributes of a system. Further, it has identified a series of trends of evolution and inventive strategies (Reference 2 again) that have previously been used to overcome such contradictions in ways that do not result in compromises and trade-offs. It is the thesis of this paper that this finding and the resulting trend and inventive strategy tools should have a significant role to play in helping organisations to deliver mass-customization solutions that avoid the traditional trade-offs. The paper examines some of the tools and then examines a number of case study examples of how they are being deployed in the mass-customization context.

Win-Win Resolution of Conflicts and Contradictions

The 2000 person years of research that has been devoted to finding inventive strategies to innovative problems has examined all fields of human endeavour and thus far – from analysis of over 3 million such solutions – found just 40 different ones. This is not to say that there aren’t more waiting to be discovered, but merely that wherever we look today – architecture, technology, biology, arts, business, etc – there are only these 40 strategies in operation. Reference 3 provides details of the 40 strategies in the context of their presence in the different fields of endeavour.

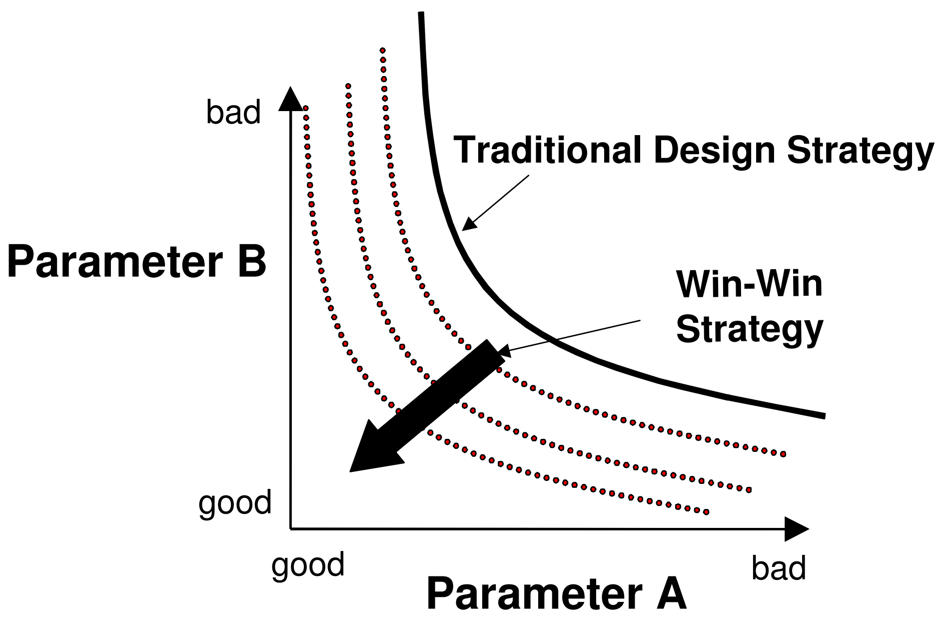

Figure 2: Win-Win versus Trade-Off Based Trade-Off Resolution Strategies

What all 40 are intended to do is to enable system designers to shift out of the conventional trade-off mentality towards a win-win goal. In terms of the trade-off map illustrated in Figure 2, the strategies detail ways of shifting the trade-off curve towards a point where a conflict has been totally eliminated. Some of the strategies may be seen to be stronger than others in terms of the degree of movement of the trade-off curve that they offer. The strategies offering the biggest jumps – and simultaneously the ones that offer the strongest solutions in a mass-customization context – are the ones that will form the focus of the following case studies:-

Strategy 15 – Dynamics (*A. Allow a system or object to change to achieve optimal operation under different conditions, B. Split an object or system into parts capable of moving relative to each other, C. If an object or system is rigid or inflexible, make it movable or adaptable, D. Increase the amount of free motion)*. In the mass-customization context, this strategy is most closely associated with increasing the adaptability of the product or service to suit the needs of different customers, rather than reducing cost per se.

Strategy 19 – Periodic Action (*A. Replace continuous actions with periodic or pulsating actions, B. If an action is already periodic, change the periodic magnitude or frequency to suit external requirements, C. Use gaps between actions to perform different useful actions).* In many senses similar to Principle 15 above, but more heavily focused on introducing adaptation to a product or service in a time as opposed to special sense. There are many examples (Reference 1) of Principle 19 being used to both increase adaptability of a product and simultaneously reduce its cost.

Strategy 25 – Self-Service (*A. Enable an object or system to perform functions or organise itself, B. Make use of waste resources, energy, or substances).* A strategy that points very directly to the word 'self' and systems that are capable of delivering useful functions (like adaptation) without the need for external mechanisms or control systems. See Reference 4 for more details about the importance of 'self' across the whole of systematic innovation.

Strategy 28 – Mechanics Substitution (*A. Replace an existing means with a means making use of another sense (optical, acoustic, taste, touch or smell), B. Introduce electric, magnetic or electromagnetic fields to interact with an object or system. C. Change from static to movable, fixed to variable, and/or from unstructured to structured fields).*

Figure 2 suggests that the shift towards trade-off elimination is a progressive process involving successive applications of the inventive strategies. The implication here is that there are benefits to be achieved by applying the strategies in combination with one another. Thinking specifically about the mass-customization issue and the importance of adaptive solutions, some of the trends of evolution that have been uncovered during the systematic innovation research identify patterns of evolution in which the highly repeatable evolution jumps made by using similar combinations of inventive strategies may be seen. Figure 3, for example, is a trend associated with the manner in which many systems (from cutting tools to automotive transmission systems to lawnmower blades to distance measuring devices) have been observed to evolve in terms of their ability to adapt to different operator situations and conditions.

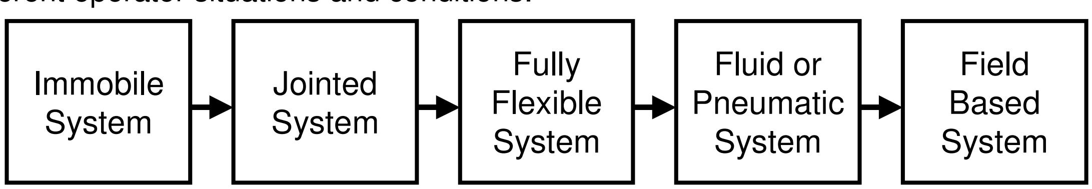

Figure 3: Adaptation and Dynamisation Evolution Trend

This trend can be seen as a combination of directions suggested by inventive strategies 15 and 28; suggesting both the incorporation of adaptive movement in systems, plus a shift away from mechanical to more fluid and then field-based solutions. Relative to mechanical systems, field-based systems (magnetic, electrical, etc) tend to be offer customers greater ability to adapt to varying needs, and make better use of resources – and hence tend to simultaneously reduce manufacture cost and harmful waste.

Another trend of evolution uncovered during the research pertains even more explicitly to the increasing adaptability of systems. Figure 4 illustrates the ‘smart materials’ trend. Again, although this trend is more recent, it is apparent that many systems have followed similar evolution strategies with, at each evolution stage jump, a net benefit to the user in terms of adaptive behaviour and thus the ability to make one system deliver the different benefits desired by individual users.

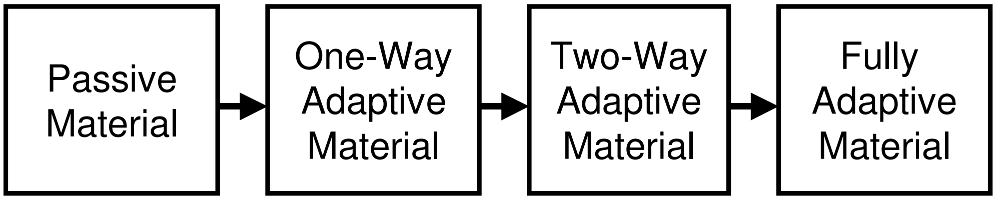

Figure 4: Smart Materials Evolution Trend

The key purpose of these trends (and the other 33 found in Reference 2) is not so much to reverse engineer what has already been achieved, but rather to identify systems that have not yet used all of the available trend stages in order that, by making the jumps suggested by the trend, new benefits can de delivered to customers.

The smart materials trend is best used in combination with resource checklists of adaptive materials. Such checklists have also been compiled during the research programme. Table 1 illustrates a simplified version of the adaptive materials resource list featuring resources relevant in the mass-customization context. They are important because they enable users to deliver solutions that inherently solve contradictions – particularly of the physical sort, where we want conflicting attributes – stiff and flexible, hot and cold, big and small, weak and strong, attract and repel, on and off, etc.

Asymmetry, local-modification to geometry Voids – bubbles, negative or variable Poisson’s Ratio
Constant fields, variable fields Oscillating Fields – frequency, amplitude, phase, compound Pulsating Fields – period, amplitude, duration, compound Resonance – natural frequency, higher order harmonics, Travelling wave – single, multiple, compound
Variable Taste/ Odour Colour change – thermo, electro, photo, pressure Variable transparency/opacity – thermo, electro, photo Variable Luminescence/fluorescence Variable Friction coefficient Deformable – tension, compression, torsional Breakable – fuse, fail-safe, designed weak-points Ferromagnetic – solid, powder, ferro-fluids Piezo-electric – forward and reverse, variable, dielectric Variable viscosity – electro-rheological, rheopexic Anisotropy X-ray/Radiation sensitive Electrical conductivity – super-conductivity, semi-conductive, variable Chemically reactive – exothermic, endothermic, reversible Liquid – absorbent, repellent Variable Bio-compatibility Variable Adhesive –triggered by water, light, air, pressure, temperature

Table 1: Adaptive Materials Resource Check-List

The paper now moves on to look at a number of case studies in which these trends, inventive strategies and adaptive resources have been applied to help create win-win solutions to typical mass-customization problem settings.

Case Study 1 – Self Balancing

The first case study to be considered involves a subject that has been discussed on several occasions in systematic innovation texts (see Reference 4 for example). The focus of the situation is the balancing of systems designed to rotate. These systems can span a range from jet engines to electric toothbrushes from washing machines to car wheels. In each case, designers have to make considerable compromises in order to achieve 'acceptable' performance of these systems. This is particularly evident when attempting to design for reliability over long periods of time when things within the system may change and thus create out-of-balance loads and forces. In the case of the toothbrush, it is desirable to be able to switch heads on the brush such that multiple users can use the same motor. Multiple users means a degree of variation in the type of brush present and the manner in which the brush is utilised – both of which lead to design compromises. In the case of the washing machine, the out-of-balance problem exists from day one since the manufacturer has no control over the loads of washing that are inserted into the machine. The compromise generally adopted in this situation involves the addition of large masses of concrete into the machine in order to ensure that it remains fixed in one place on the ground during high-speed spin cycles with large out-of-balance loads. While concrete is not in itself expensive, transporting it to customers and problems of handling installation often can be. As far as car wheel balancing is concerned, the compromises exist on the car (the need for unsightly lead weights attached to the wheel), at the garage (where there is a need for expensive equipment to balance wheels) and at the manufacturer (which has to make several subtle but nevertheless important compromises when designing the car to be able to operate reliably over prolonged periods when things might be out-of-balance).

All of these problems would disappear, of course, if the rotating assembly were able to balance 'itself'. As it happens, several inventors have developed self-balancing solutions. Unfortunately, very few of their solutions have made the shift from where they were developed to other sectors. Figure 5, for example, shows a patent that was granted over ten years ago. Although it is in itself a comparatively complex solution to the problem, it nevertheless serves to illustrate a general concept that can quite readily be transferred to other sectors in which different customers have different system operating regimes and thus would benefit from systems that adapted to their specific way of doing things. The patent relates to a device for delivering self-balancing properties to a car wheel. The basic principle contained in the invention is that a rotating part of the system (component 2 in the figure) is designed to contain other parts that are able to move relative to the first part (component 4 in the figure – actually in this case ball-bearings). The self-balancing capability is produced when the ball-bearing components move relative to the main rotating component in such a way that they naturally position themselves to counter any out-of balance forces. The solution manages to use inventive strategies 15 and 25. Reference 4 contains a more detailed description of precisely how the solution delivers self-balancing capabilities for those interested in finding out more.

As suggested, the Figure 5 solution is actually rather more complicated than it needs to be – containing not only ball-bearings, but also a damping fluid, and indeed the whole ring component (2) is something added to a wheel rather than using an existing resource on the conventional wheel. Some readers may in fact be familiar with a much more simple solution to this self-balancing wheel problem – a handful of sand thrown into the cavity inside the tyre produces precisely the same effect with no adverse consequences. (Apart from being more difficult to sell commercially!)

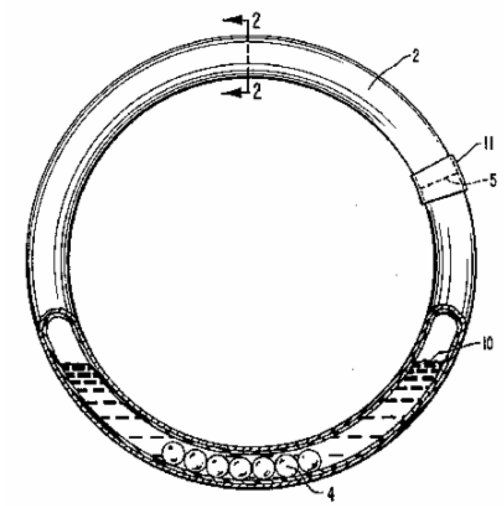

Figure 5: Typical Self-Balancing Rotative System

The points of this case study are first to register the fact that because balancing is traditionally such a problem area, it is highly likely that there will be someone will have thought about self-balancing (as it happens, as long ago as the early 1970s as far as the patent record is concerned). Second is the need to register the fact that the elegant self-balancing concept hinted at in the Figure – enable small unconstrained things to move, position and re-position themselves relative to a bigger rotating thing – can be applied in many design situations where adaptability to different conditions is a useful customer benefit.

Case Study 2 – Self Adapting

Manufacturers of clothing or footwear traditionally force the consumer to make a broad range of compromises in order to be able to use mass-manufacture techniques that will keep prices at an affordable level. Every human is slightly different from every other and so what is right for one person is unlikely to also be precisely right for another. This type of compromise problem is traditionally solved by manufacturing goods in a range of sizes, fits and styles. Such solutions present manufacturers with a number of trade-offs in terms of product inventory versus being able to offer customers as many options as possible. In terms of footwear, despite the possibility of a vast combination of size and width fittings, shoe wearers are nevertheless still faced with the need to compromise on some aspect of the shoe they buy. Not least of which is the fact that over the course of a typical day, the human foot can change shape by one or two-sizes. The footwear industry typically forces consumers into trade-off choices like 'size 9 or size 10'. Or, if it's an expensive shoe, maybe also a 9½ - another compromise. In TRIZ terms, this is a trade-off that could be avoided if the shoe was 'size 9 **and** size 10'. This contradiction could be solved if the footwear was able to adapt to become whatever size was required at any given time. Even better would be a design in which the footwear itself was able to adapt to suit the local requirement.

This kind of self-adapting footwear – if it could be achieved – would not only solve the inventory problems that play a dominant role in the industry, but also deliver customers a product that both fit better, and also fitted equally well as the shape of the foot changes. It transpires (of course!) that someone has again been thinking about these problems with a mindset that seeks to eliminate the compromises. The slipper illustrated in Figure 6, for example, contains rheopexic gels that cause the slipper to mould (and re-mould) to the changing shape of the foot of the user.

Figure 6: Self-Adapting Slipper (Reference 5)

This case study is a relatively simple, albeit important one from the perspective of adaptive systems and the idea of mass-customization. The principle learning point offered is the importance of effects like the rheopexic gel that deliver adaptive capabilities to systems. Here, the resource checklist elements outlined in Table 1 are extremely important in enabling users to identify systems capable of delivering self-adapting and other self-x functions.

Case Study 7 – Self Creating

One of the reasons that mass-customization has been possible in the world of software systems is the shift from mechanical to field-based systems suggested by the Figure 3 dynamization trend. Put simply, it is very much easier and cheaper (programming cost usually being the only required expenditure) to create adaptive capabilities in software rather than hardware. There are very many examples of commercial software packages that offer users the ability to tailor both the appearance and functionality they receive.

Looking a little further ahead than this common type of mass-customization adaptability is one of enabling systems to not only adapt by themselves, but also to 'create themselves'. In life systems found in nature, such a function is only indirectly achieved through some form of reproduction; the concept is still very new from a software perspective, albeit one strongly driven by ideality-driven thinking.

If the idea of self-creating software sounds a little far-fetched, we conducted a short exercise using the generic CreaTRIZ problem explorer 'Define Pack' (Reference 6) to help structure thinking on the possibilities of such a capability. The results of that exercise are reproduced in Figure 7. The main purpose of the structure is to recognise that even if the IFR cannot be achieved, it is still often possible to step back from this definition to a solution that is still beyond the paradigm's defined by the current state of the art.

As is usual with the 'start from the end and work back towards the achievable' thinking framework suggested by the systematic innovation research, the first issue having defined the chain of events leading back from the IFR definition was to examine the viability of the ultimate IFR definition. These explorations lead to the work of Robonetics NV of Belgium (Reference 7), who are trying to make self-generating software systems that will create other software systems. The company specializes in providing tools and services for Artificial Intelligence and Robotics. The recent announcement of their Robot Intelligence Definition Language™ (RIDL™) sees the first release of their self-creating software capability.

Agent-Based Software Engineering tries to model software using agents. To take one simple example, when attempting to model the stock market, one considers a stockbroker as an agent with his own set of goals, and a company with a different set of goals. Putting these together can model the complex interaction of the stock market. Unfortunately, in the past, it required complex software engineering to convert an agent-based design into an object-oriented software design that can be implemented. To make a comparison: not many people were designing object-oriented databases at a time when only relational database management systems existed. The conversion was just too time consuming. Likewise, agents are rarely used in real life software. RIDL™ is a design specification language that is built from the ground up to create agent-oriented software. Once the design is made in RIDL, code generation will automatically build the software in an object-oriented language. As part of this process, RIDL solves complex issues. Data flows are analyzed to determine the priority of each agent, execution thread reduction is used to keep systems with ten thousands of agents still executable on a single processor computer, and other conversions are performed. The end result is an object-oriented program that can be compiled directly to working code. RIDL™ supports full Agent-Oriented Software Engineering (AOSE), including agent-level polymorphism and inheritance, and support to dynamically create agents in Multi-Agent Systems (MAS). In the language of Robonetics, '*RIDL joins the designed agents into a working society that defines the mind of the computer'.*

The RIDL capability sees complexity 'emerging' from small constituent pieces of software (digital DNA?). In this sense it bears considerable similarity to the messages contained in References 8 and 9 – ideal self-x systems emerge autopoietically.

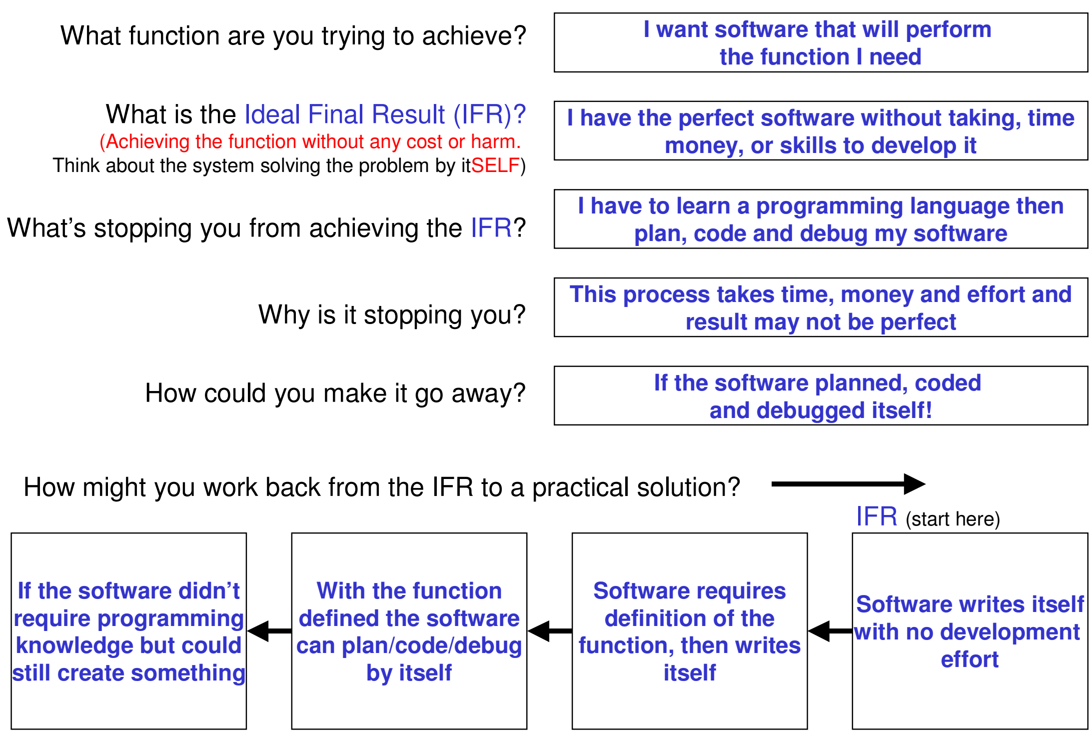

Figure 7: Self-Creating Software IFR Definition Framework

Self-creating systems perhaps represent the some kind of ultimate definition of adaptive systems, since if a system is capable of creating itself to suit a set of external requirements, it is also capable of re-creating itself to match changing external conditions – i.e. it is capable of self-adaptation. In terms of solving a parallel desire to not only increase the beneficial functions delivered to customers, but also reduce the cost and harm, the self-creating paradigm may be seen to present potentially significant reductions in programming time also. As such, it holds open the prospect of genuine win-win for both customer and supplier in the drive towards an Ideal Final Result evolution destination.

Conclusions

Systematic innovation research suggests that successful innovations evolve in a direction of increased ideality relative to their competitors. Different requirements of different customers suggest that adaptability is an important element of what increased ideality implies. The systematic innovation research has uncovered tools and strategies that enable adaptability to be achieved without compromises to other aspects of a system.

The world of design traditionally operates from a trade-off and optimisation perspective – such that the job of the designer becomes the achievement of 'acceptable' values of parameters in conflict with one another. The systematic innovation research has identified the fact that the most successful solutions do not come from such either/or strategies, but instead seek to achieve win-win outcomes in which trade-offs are progressively attacked and eliminated through the application of inventive strategies and trends of evolution. Such tools are generically applicable across a broad range of mass-customization issues.

Further increases in system ideality result from solutions capable of adapting to suit different user requirements by themselves. The concept of systems performing useful functions 'by themselves' is thus also extremely important in the mass-customization paradigm.

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