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A METHODOLOGY FOR THE EXTRAPOLATORY DESIGN OF SUPERIOR PRODUCTS

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1 Introduction

In mathematical terms, interpolation is a process for generating estimated functional values at arbitrary locations within the convex hull created by a set of data. This is the smallest net that can contain the original data set. At the original points, the estimated values will be identical to the interpolated values. Extrapolation is the extension of a curve or range of values by inferring unknown values outside the data set from the trend of the data within it. A predicted value outside the convex hull of an input data set is known as an extrapolated value. In Figure 1 the knot points P_1, P_2, P_3, P_4 and P_5 define the original data set which represent the functional values *y*, for different values of the parameter *x*, and thus the convex hull is the curve segment $P_1P_2P_3P_4P_5$. Interpolation is the process of finding the value of the function, y_I for the parametric value x_I and extrapolation is the process of finding the value of the function, y_E for the parametric value x_E.

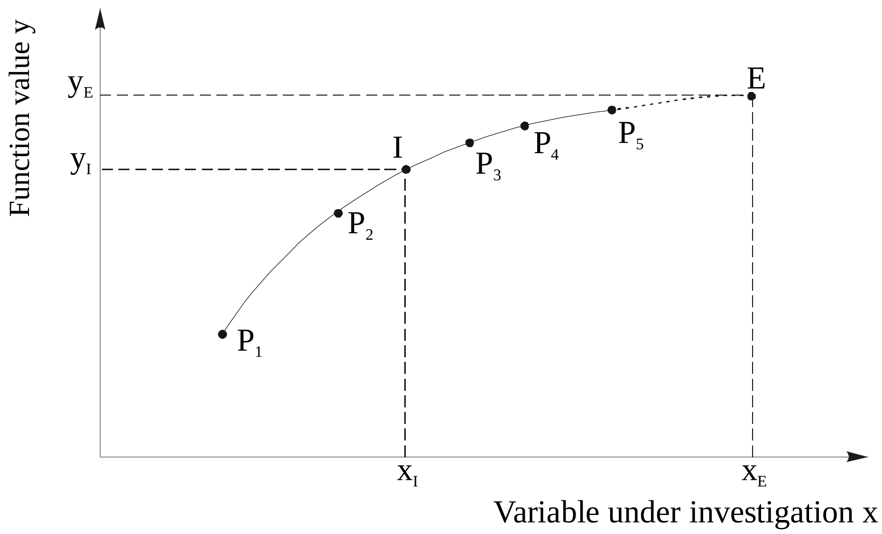

Figure 1. Interpolation and Extrapolation explained

This process can be extended to multi-dimensions where $y = f(x_1, x_2, ---x_n)$. Interpolation and extrapolation require knowledge of the functional and parametric values at the knot points to estimate points inside and outside the convex hull respectively.

In a similar fashion, a design can be treated as a point in an *n* dimensional hyperspace where each dimension is a design variable and the functional parameter (*y*) is a performance characteristic, *PC*. Thus for a design $PC = f(d_1, d_2 --- d_n)$. Knowledge from past designs is enormously influential in future designs of the same or similar products, and therefore can be considered as the knot points. Thus, designing future products can be treated as an extrapolatory process. However, the problem is the choice of the right performance characteristic and the design variable set. Mendis and Sivaloganathan [1] identified that the Design Process generates five types of information about a design at different levels of abstraction as shown schematically in Figure 2. They further identify that next generation products can be developed based on one or several of the following approaches:

1. Addition of extra requirements to make the product more efficient, effective and useful to the customer.
2. Enhancing the ‘Product Concept’ with extra functions that are made possible due to economic reasons, better insights into the problem, and advancements in science and technology.
3. Replacing the conceptual design of one or more of the subsystems with technologically better ones resulting from latest developments.
4. Changing the Embodiment Design by the combination of some of the existing parts or by replacing a collection of parts with a single better part.
5. Changing the detailed design of one or several parts.

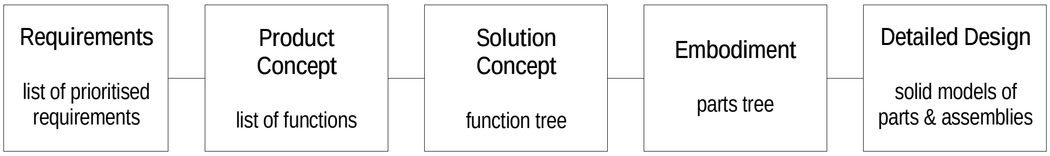

Figure 2. Design Process and Information Generation

Of the five approaches outlined above, 1) to 4) are suitable for use in the functional domain and to identify sets of design parameter values, whereas 5) because of its solution specific detail, is restricted to the physical domain.

2 Aims and Objectives

The broad aim of this paper is to establish an extrapolatory design methodology to predict future product generations by considering the designs of the past generations in the function domain. In the process the following objectives were set out:

1. Analyse the design of the first generation and extract the conceptual design in the form of a Function Family Tree (FFT) [2, 3].
2. Analyse the designs of each generation and the subsequent generation and identify the functional enhancements that have been provided in the subsequent generation and the weaknesses that have been eliminated.
3. Tabulate the chronological weaknesses and improvements provided to the product so that one can understand the trend easily and establish the design of the next generation.

3 Methodology

The key to the process is to establish the conceptual design in the form of a Function Family Tree. Mendis and Sivaloganathan [1] recommend the following steps:

1. Describe the process or the action of the product with the intention of identifying the underlying working principle.
2. From the description, establish the various subassemblies that form part of the Embodiment Design in the form of a parts tree.
3. From the Embodiment Design, establish the functions performed by the various functional subsystems, or group of functions, which forms the conceptual design in the form of a Function Family Tree.

The methodology for extrapolating the product functions into the next generation of product is shown in Figure 3.

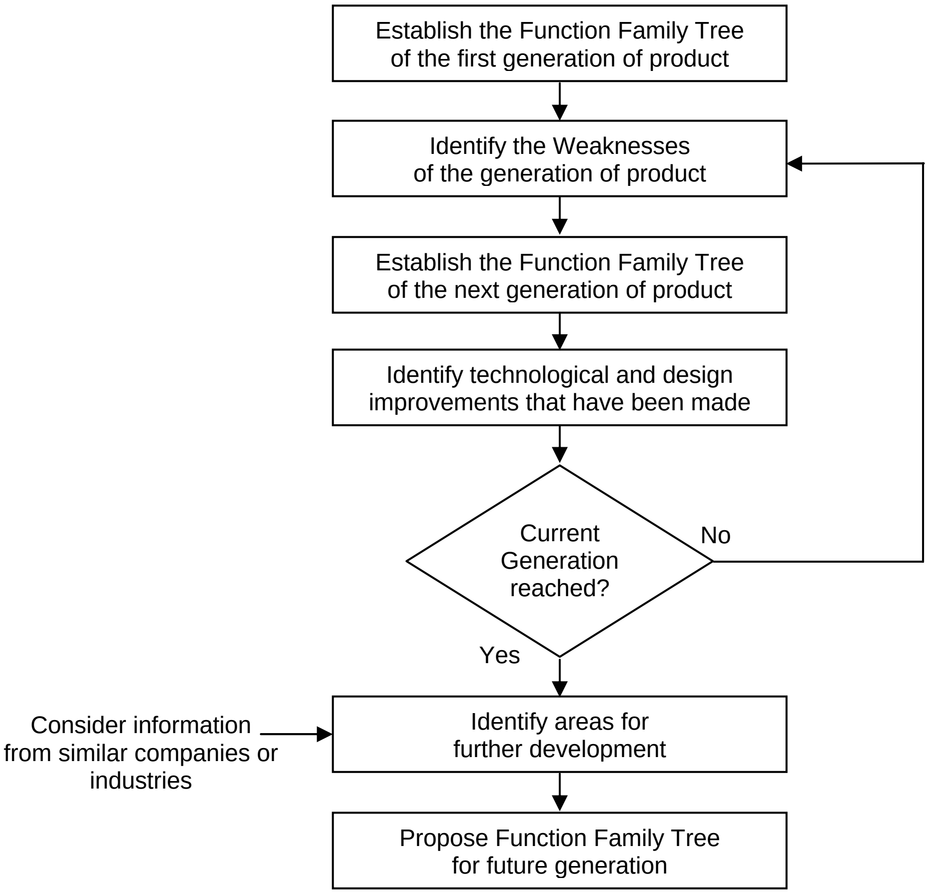

Figure 3. Extrapolatory Design Methodology Flowchart

The methodology begins by establishing the Function Family Tree of the first generation of the product. It is followed by the identification of the weaknesses and limitations of the generation. The Function Family Tree of the immediate next generation of the product is then established. The process is repeated until the current generation is reached. A table is created showing the sequence of problems and the improvements that were implemented in the past generations of the product. This summary data sets the trend for predicting the future generation of the product.

4 Case Studies

The methodology presented above is demonstrated using some practical examples. The first case study considers the development of machine tools from simple beginnings as a Lathe, to the current Computer Numeric Control Machining Centres. The second case study considers a relatively new product, the stabilisers used to support hydraulic work platforms, or “Cherry Pickers”. In each case, a prediction of the future generation product is made based on the limitations of the current generation of each product. The second example discusses the issues in applying this methodology to a newer product within a developing industry.

4.1 Case Study: Machine Tool

The methodology is demonstrated using a case study of component turning machines. Successful generations of lathes were considered, starting with Moudslay’s lathe. Function family trees for each generation i.e. Moudslay’s lathe, Centre Lathe, Turret Lathe, NC lathe and horizontal machining centres were established. The problems facing each generation of lathe were examined and technological advancement opportunities were identified. This formed the basis for extrapolation. The FFT of a particular generation (say the Turret) shows the design point outside the convex hull created from the previous generations (Moudslay’s and the Centre Lathe). Table 2 shows the functions that appear in each generation of machine tool, and in which generation each function first appeared.

The analysis of lathe generations is presented in Table 2, which identifies that the significant reasons preventing customers purchasing Machining Centres are (a) high initial capital investment and (b) high volumes of parts needed to use capacity or amortization of initial investment would increase product unit costs. This suggests that if machines can be hired for short periods when required, companies could avoid the large capital investment, and continuous large quantities of work would not be needed.

Thus from this analysis it is predicted that machine tools that can be easily rolled-in and rolled-out of factories is the way forward. However, this requires a transportable machine tool that could be made operational in a short time. The additional functions *allow easy transportation; allow rapid set up;* and *easy to use (Minimise training needed)* would be required from the next generation machining centres. This is represented in Table 1 by the right hand column that shows that the next generation will include the functions of the current generation plus the new functions stated above.

Table 1. Functions of Different Generations of Machine Tools (Note: ticks indicate the presence of a function. Bold ticks indicate that function's first appearance in a turning machine. The right hand column is the extrapolated prediction).

	Functional Sub-System	**Function**	**Moudslay's Lathe**	**Centre Lathe**	**Turret Lathe**	**NC Machine**	**CNC Machining Centre**	**Next Generation**
CNC Machining Centre	Controller	Control Movements of Servo Systems					✓	✓
		Compute cutter paths and positions					✓	✓
		Start and Stop various spindles				✓	✓	✓
		Select correct spindle speeds and sequences				✓	✓	✓
		Control auxiliaries such as coolants				✓	✓	✓
		Select and perform tool changes					✓	✓
		Select and perform pallet changes					✓	✓
		Provide Mechanical stops and trips (Memory)			✓	✓	✓	✓
		Load and unload different work programmes.				✓	✓	✓
	Servo Systems & Drives	Power drive the various spindles		✓	✓	✓	✓	✓
		Introduction of multiple spindles					✓	✓
		Drive tool changing mechanism					✓	✓
		Drive pallet changing mechanism					✓	✓
		Move tool holding mechanism				✓	✓	✓
		Perform basic relative motion	✓	✓	✓	✓	✓	✓
	Bed	Provide rigidity	✓	✓	✓	✓	✓	✓
		House the various moving columns, spindles, carriages etc	✓	✓	✓	✓	✓	✓
		Provide easy swarf and coolant collection		✓	✓	✓	✓	✓
		House the various auxiliary services		✓	✓	✓	✓	✓
		House the various slide-ways			✓	✓	✓	✓
	Tool Magazine & Tool Changer	House various tools					✓	✓
		Provide standard tool holding	✓	✓	✓	✓	✓	✓
		Provide multiple Tool holding			✓	✓	✓	✓
		Provide easy access to different tools					✓	✓
		Provide easy grip and changing mechanism					✓	✓
		Provide automatic indexing of tools					✓	✓
	Palletizing & Work Changing	Provide indexed pallets					✓	✓
		Provide easy work holding fixtures					✓	✓
		Provide indexed palette changing					✓	✓
	Transportation	Allow easy transportation						✓
		Allow rapid set up						✓
		Easy to use (Minimise training needed)						✓

Table 2. Comparisons between different generations of machine tools

Machine Tool and Main Functions	Problems and Limitations	Solution by Next Generation
Moudslay's Lathe Turn work piece and feed tool at predefined rate and depth of cut to produce cylindrical surfaces	Manual process, not very accurate, no change of speeds at definable range.	Power driven gearboxes to provide accurate movements as set by the operator
Centre Lathe Power driven machine for production of cylindrical surfaces at changeable feed rates, depths of cut and speeds	Operator controlled, hence vulnerable to error as no machine memory	Mechanical trips and stops
Turret Lathe Power driven machine for production of cylindrical surfaces with multiple tools and mechanical memory devices	Partial requirement for operator input and high set-up time, hence large batch size. Set-up cannot be repeated.	Predefined operations and parameters controlled by tapes or punched cards.
NC Lathe Power driven machine for production of cylindrical surfaces with multiple tools with MCU control using tapes or cards	Inflexibility of tape, damage to tapes	Computer control with changeable programs
CNC Lathe Power driven machine for production of cylindrical surfaces with multiple tools controlled by computer program.	Operations limited to traditional grouping of machine tools. Did not exploit fully the advancements in computers and cutting tools	NC machines capable of performing several functions from several traditional machine groups at high speeds.
NC Machines Multi axis NC machines capable of several functions from several traditional machine groups at high speeds.	Long set-up, work loading and unloading	Machining centres with tool magazines and palette changing facilities
Machining Centres Multiple Axes Machining centres with tool magazines and palette changing facilities	Very expensive, high capacity requiring a lot of work. High level of training needed	WHAT CAN BE DONE?

4.2 Case Study: Access Platform Stabilisers

The lathe case study above has demonstrated how Extrapolatory Design can be applied to a mature product whose requirements are well established. A second case study, the stabilisers of Hydraulic Work Platforms or "Cherry Pickers", will examine a product that is evolving relatively quickly, and has a number of current states from different companies in the Powered Access Industry.

The stability of hydraulic work platforms is key to their safety, and the role of the stabilisers is to prevent the machine from turning over, thus allowing a maximum mass of operators and equipment to move safely within the working envelope of the machine.

The authors humbly point out, that only a representative sample of the existing designs is possible within the scope of this paper. Furthermore, a thorough investigation would consider the stabilisers of other similar products such as cranes, fire engines and telescopic materials handlers. In this example, the majority of designs are from Company A, with one from Company B to demonstrate that multiple current generations exist within one industry.

The first generation stabiliser design from Company A is shown in Figure 4 and its Function Family Tree is presented in Table 3. The embodiment of the first system was indeed basic: Four stabiliser fabrications had to be slid from within the base fabrication's housings, located, and then the feet wound down appropriate amounts to level the machine. Limitations of this design were: Significant manual effort and limited ability to level the machine. In addition, regulatory requirements were not developed at this time, and users were not sufficiently experienced in using the machinery to know, in significant depth, what they wanted. This situation changed quickly, leading to the improvements of the second, third and fourth generation stabilisers.

Figure 4. 1A (1st Generation Stabilisers by Company A) Manual Winding

Table 3. Function Family Tree for 1A (1st Generation Stabilisers by Company A) Manual Winding

	Functional Sub-System	Function
Manual Winding Stabiliser	Winding Mechanism	Allow adjustment of foot position
		Provide mechanical advantage
		Resist vertical movement
	Stabiliser Fabrication	Resist load
		Transfer load to base
	Foot & Ball Joint	Allow foot to rotate
		Resist vertical reaction
		Spread force across ground

The major limitation of the first generation of stabilisers was safety. It was possible to set-up the machine incorrectly and then activate the boom structure, possibly leading to toppling. In the second generation that followed promptly, a safety switch was introduced into each stabiliser to alert the user if a foot was light, enabling corrective action to be taken thus improving user safety. Regulations soon followed to make this compulsory.

Table 4. Function Family Tree for 2A (2nd Generation Stabilisers by Company A) Manual with Safety Switch

	Functional Sub-System	Function
Manual Winding Stabiliser with Safety Switch	Winding Mechanism	Allow adjustment of foot position
		Provide mechanical Advantage
		Resist vertical movement
		Resist movement
	Stabiliser Fabrication	Resist load
		Transfer load to base
	Foot & Ball Joint	Allow foot to rotate
		Resist vertical reaction
		Spread force across ground
	Switch & Spring	Prevent boom function if stabilisers incorrectly deployed.
		Indicate if foot goes light during operation of machine.

The second generation of stabilisers improved user safety, but the market soon demanded an alternative because of the significant manual effort required to set-up the machine. This was resolved in the third generation of stabiliser by using including a hydraulic cylinder to deploy and retract the stabilisers as shown in Figure 5. This enabled the machine to be set-up by the user from a single location using a control valve.

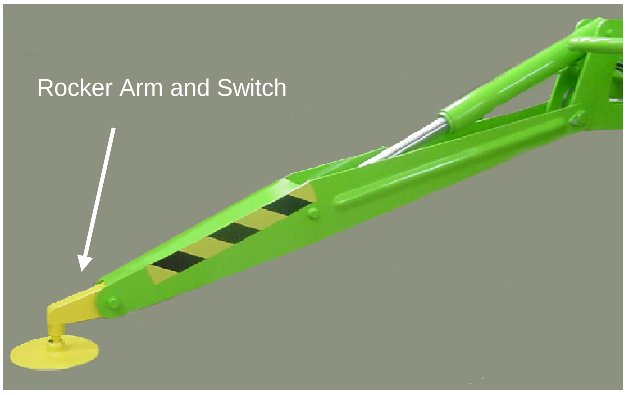

Figure 5. 3A (3rd Generation Stabilisers – Company A) Hydraulic Powered

Table 5. Function Family Tree for 3A (3rd Generation Stabilisers – Company A) Hydraulic Powered

	Functional Sub-System	Function
Hydraulic Stabiliser	Hydraulic Cylinder & Control Valve	Allow adjustment of foot position
		Provide mechanical advantage
		Allow machine set-up from one position
		Resist movement
		Transfer load to base
	Stabiliser Fabrication	Resist load
		Transfer load to base
	Foot & Ball Joint	Allow foot to rotate
		Resist vertical reaction
		Spread force across ground
	Switch & Spring	Prevent boom function if stabilisers incorrectly deployed.
		Indicate if foot goes light during operation of machine.

It is at this stage that the basic requirements of the stabiliser system matured, leaving improvements to be made in usability and manufacturing.

The analysis at this point becomes more difficult, as the current generation of one company is not always the same as that of another, leading from a one-to-many relationship to a many-to-many relationship between current generation and future generation. This is to be expected, however, as companies within the same industry may target niches with different requirements, calling for a different technology strategy; for instance, the use of hydraulic controls instead of electric controls addresses a user preference for ease of maintenance, but limits the options available to the manufacturer in the embodiment of the system.

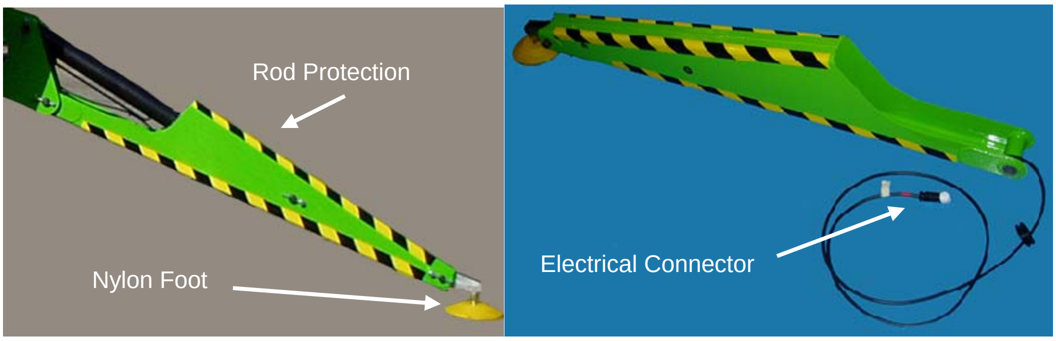

Figure 6. 4A1 (4th Generation Stabilisers, Company A, Type 1) Hydraulic Powered, Integral rod protection and manufactured as sub-assemblies (Right)

Table 6. Function Family Tree for 4A1 (4th Generation Stabilisers – Type 1 - Hydraulic, rod protection and non-marking feet.)

	Functional Sub-System	**Function**
Hydraulic Stabiliser with integral rod protection and Nylon Feet	Hydraulic Cylinder & Control Valve	Allow adjustment of foot position
		Provide mechanical advantage
		Allow machine set-up from one position
		Resist movement
		Transfer load to base
	Stabiliser Fabrication	Resist load
		Transfer load to base
		Protect cylinder rod from falling debris
	Foot & Ball Joint	Allow foot to rotate
		Resist vertical reaction
		Spread force across ground
		Prevent marking or damage to surfaces
	Switch & Spring	Prevent boom function if stabilisers incorrectly deployed.
		Indicate if foot goes light during operation of machine.
		Allow modular assembly

The fourth generation, type 1 stabiliser from Company A, shown in Figure 6, has a cylinder rod protector as part of the stabiliser fabrication, preventing damage to the rod from falling debris. Other improvements of this generation include non-marking nylon feet and the ability to manufacture the leg as a sub-assembly because of the modular design of the electrical control system.

In addition to the single stabiliser design, Company A has developed an alternative design comprising a two-stage stabiliser leg. This is presented in Figure 7 and the Function Family Tree is in Table 7. This design allows increased penetration and spread than is available from a single leg. Although the major functions for this leg are similar to all other hydraulic legs, the embodiment design is significantly different.

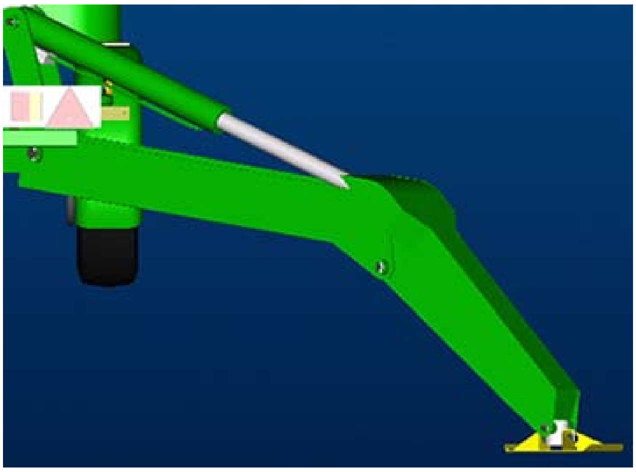

Figure 7. 4A2 (4th Generation Stabilisers, Company A – Type 2 - Hydraulic, two-stage stabilisers)

Table 7. Function Family Tree for 4A2 (4th Generation Stabilisers – Type 2 - Hydraulic, two-stage stabilisers)

	Functional Sub-System	**Function**
Hydraulic Stabiliser with two-stage fabrication	Hydraulic Cylinder & Control Valve	Allow adjustment of foot position
		Provide mechanical advantage
		Allow machine set-up from one position
		Resist movement
		Transfer load to base
	Stabiliser Fabrications	Resist load
		Transfer load to base
		Protect cylinder rod from falling debris
	Foot & Ball Joint	Allow foot to rotate
		Resist vertical reaction
		Spread force across ground
	Switch & Spring	Prevent boom function if stabilisers incorrectly deployed.
		Indicate if foot goes light during operation of machine.
		Allow modular assembly
	Deployment Mechanism	Synchronise deployment with cylinder extension
		Open stabiliser at knee joint

Another consideration in this analysis is to examine what other companies have as their current generation. Figure 8 is a stabiliser design from Company B that at first glance seems similar to the 3rd Generation from Company A. Closer examination shows that the embodiment is subtly different, in that the load sensing function is performed by the leg pivot pin moving in a slotted hole to activate the switch, rather than a rocker arm and switch. This system is lighter and likely to be cheaper as there are fewer parts.

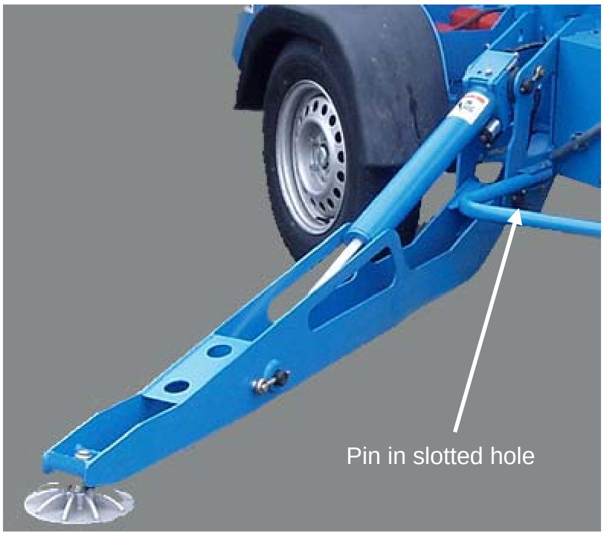

Figure 8. 4B1 (4th Generation Stabilisers, Company B – Type 1 - Hydraulic, sliding pin sensing)

Table 8. Function Family Tree for 4B1 (4th Generation Stabilisers, Company B) Hydraulic, Auto Levelling

	Functional Sub-System	**Function**
Hydraulic Stabiliser with Auto Levelling	Hydraulic Cylinder & Control Valve	Allow adjustment of foot position
		Provide mechanical advantage
		Allow machine set-up from one position
		Resist movement
		Transfer load to base
		Allow one touch setup
	Stabiliser Fabrications	Resist load
		Transfer load to base
		Protect cylinder rod from falling debris
	Foot & Ball Joint	Allow foot to rotate
		Resist vertical reaction
		Spread force across ground
	Sliding pin in housing	Prevent boom function if stabilisers incorrectly deployed.
		Indicate if foot goes light during operation of machine.

Table 9 summarises the key functions of the recent generations and states the limitations of the current generation of stabilisers. Whilst the new generation of lathes contained all functions from previous generations, the stabilisers are still maturing and do not carry forward all the functions from the previous generations.

In addition, it is noteworthy that some functions may not change in the extrapolation. Once some functions' performance reaches a certain level, there may be physical limits or diminishing returns from attempting to develop them further. For instance, *spread load* seems to have reached acceptable pressures for most applications and the size of stabiliser feet does not vary greatly between machines of the same mass.

Table 9. Stabiliser Generations for Access Platforms

Generation	Description	Limitation	Solution by next generation
1A	Manual Outriggers	Slow to deploy, limited spread and can only level machine on small angles. Possible to setup machine without all legs deployed correctly.	Safety switches ensure stabilisers are deployed correctly, preventing use of the booms if a foot is light.
2A	Manual Outriggers with safety switch	Time consuming to deploy and requires significant manual effort	Hydraulic cylinders allows machine to be set-up from one location.
3A	Hydraulic stabilisers with Metal Feet	Slow to assemble, cylinder rod prone to damage as exposed. Feet damaging to surfaces and rust after use. Time consuming to build.	Integral rod protection within stabiliser fabrication. Brightly coloured Nylon feet.
4A 1	Hydraulic outriggers with integral rod protection. Quick release connectors enable subassembly. Nylon feet reduce damage to flooring.	Time consuming to set-up. Many parts.	One touch set up levels machine automatically, deskilling the task.
4A 2	Two section stabilisers for increased spread and penetration from a given stowed height	Many parts, expensive.	What can be done?
4B1	Auto-levelling (Done by some companies but not Company A).	Cost. Limited adoption by the market.	What can be done?

The next generation of Access Platform Stabilisers

One limitation of the current generation is the need to optimise the overall machine function speed of the stabilisers, boom lifting and extension, and rotation to be within their respective maximum speeds set by regulations, and their minimum speeds defined by users' patience. Hydraulic machine control solutions, favoured by many customers because of easy maintenance, are inherently limited in their ability to vary flow. A limitation of the current generation of machines is to produce exactly the flow that is needed to optimise each function. One option is to change from a fixed displacement pump to a variable displacement swash plate pump, but this incurs high costs and requires electrical or electric-over-hydraulic control. A separate dedicated pump could be set aside for stabilisers whilst another is used for booms, but on Bi-Energy or Dual Fuel machines where an engine is used alongside batteries or mains power, this would require four pumps instead of two, which is costly again. Instead of individual pumps, tandem pumps could produce different flow rates by either using, one the other or both pumps, but once again, this needs electric control. A change in strategy to electric control carries with it significant market risk, but a voltage regulator on a DC motor would allow variable flow from a gear pump, by changing motor speed. On a Bi-Energy system, a second speed regulator would also be required on the engine, which currently run at one speed.

Another option, which is independent of the control system chosen, is to use regenerative valves on the double acting stabiliser cylinders, to return the annulus oil volume into the full bore side of the cylinder. In this way, the stabiliser can function faster as only the rod volume is required to extend the cylinder. This change in speed of extension for a given flow rate of oil, should bring the operation of the stabilisers much closer to the flow rate demanded by the booms, and does not depend on the power system chosen for the machine or the control preference of the customer.

Another limitation of the current generation of stabilisers from Company A, is the mass of the switching system. A lighter weigh and seemingly cheaper solution to this has been used by Company B, and could be used to implement the next generation of stabiliser.

It is therefore predicted, that the next generation of single stage stabiliser will use the integral cylinder rod protection and non-marking feet of the current design by Company A, the alternative load sensing method leading to cost and mass reduction by the current design of Company B, along with regenerative valves to improve deployment speed. This is an extrapolation of the progression from winding mechanisms to hydraulic cylinders for faster deployment and ease of use. Automatic levelling is likely to be demanded by the market to further improve ease of use, but the additional cost suggests that this would be a customer option for those companies willing to mass customise. Those that intend to provide only a standard product will have to bear the additional cost within that standard product. Whether or not to challenge a competitor within a given sector is often a business decision rather than a technical one. Christensen et al [4] discuss “litmus tests” that should be considered when identifying and building disruptive new businesses.

The two-stage stabiliser 4A2 could be improved for the next generation by reducing the part count and considering alternative embodiments for the deployment system. Deployment speed for this larger design is not a problem because of the larger power systems fitted to bigger machines. This design is young, as rarely is so much spread required from a small stowed space.

5 Advantages of using the Methodology

In addition to the primary role of the methodology, to identify the next generation product, there is also likely to be a benefit to organisational knowledge if this approach is implemented.

Analysis of a product’s history and storage of information in a Function Family Tree allows companies to record knowledge about their products succinctly in one location. Knowing the limitations of a particular design and how a problem has been rectified reduces the risk of the company repeating mistakes. Explicit storage mechanisms such as this, also go some way to avoiding the problem of tacit knowledge, which can be a significant loss to an organisation when experienced staff leave the company or move projects. Creating a Function Family Tree for each generation of a product and a table of limitations is a concise way to summarise how the design has developed over time. The design intent of each generation and the reasons for making decisions could also be stored if this methodology were supported by established design methods [5], such as the Marples Decision Tree [6] and the Pugh Concept Evaluation and Evolution Technique [7]. An engineer new to the next generation project or to the company, would then have a solid foundation on which to base future work, without having to “reinvent the wheel”.

6 Conclusion

A methodology for the extrapolatory design of superior products has been established and demonstrated with two case studies: Lathes and Access Platform Stabilisers.

Extrapolatory Design using function analysis and the limitations of product generations can be used to predict alternative future designs of the same product.

Predicting future directions for a product is difficult, and market conditions and new technological advancements affect the direction taken. Pugh Concept Evolution and Marples' Decision Tree could be effective both to evaluate alternative future next generation products, as well as recording information to develop organisational knowledge.

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