

Small is Beautiful: Engineering as if People and Environment Mattered

Karthikeyan Subramanian, John Olsen, Erik van Voorthuysen
School of Mechanical and Manufacturing Engineering,
The University of New South Wales.

ABSTRACT

This paper discusses recent thinking on the topic “Small Is Beautiful” and how this may apply to manufacturing. With advances in robotics and automation, control systems and vision, the downscaling of processes may become technically and environmentally feasible. This paper presents the concept of scalability as it applies to manufacturing processes. It examines economic, technical and social factors that influence the so called “optimum plant size” and looks at the development of technology so as to suggest ways to realise downscaling.

INTRODUCTION

There is evidence, worldwide, of problems associated with large scale manufacturing processes including suboptimal OEE (overall equipment effectiveness), equipment life, productivity and utilization. Social and environmental costs associated with large scale manufacturing and distribution infrastructure are also substantial. Examples include regional unemployment, pollution, transportation costs and traffic congestion. As a consequence, there has been a re-emergence of discussion on the topic of downscaling and Schumacher’s “Small Is Beautiful” concept (Schumacher, 1999) and how these may apply to manufacturing.

The philosophy behind this research is the development of low-cost appropriate technology specifically aimed at downscaling processes for the benefit of small to medium enterprises (SMEs). Some major enablers of this technology are low-cost and high performance control, actuation and sensor technology as well as emerging design technology. This paper proposes a scalability index that can be used to analyse and assess the extent to which a given process can be downscaled.

The traditional Fordian concept of mass production coupled with advanced process control, automated materials handling, and sophisticated design, scheduling and costing software has accelerated the proliferation of large, centralized, global manufacturing plants that are now increasingly able to combine mass production with customization and to do so economically. At the same time this has seen the inevitable demise of SMEs in most generic markets. Conventional break-even and payback analyses are used to determine the optimum level of investment in plant and equipment within the supply chain to balance economies of scale against transportation costs and product differentiation.

Mahatma Gandhi, the prominent leader of the last century was perhaps first to raise an alarm on the trend of production calling for “production by the masses instead of mass production”. Mass production he felt would not be compatible with man’s need for creativity. He suggested that technology go back to the actual size of man: *“We need methods and equipment which are cheap enough so that they are accessible to virtually everyone; suitable for small-scale application and compatible with man’s need for creativity. The poor in the world cannot be helped by mass production, only by production by the masses; technology should go back to the actual size of man” - Mahatma Gandhi. (Ishii, 2003).*

Schumacher (1999) boldly stated that: *“The most fateful error of our age is that the problem of production has been solved. This is the view held virtually by all experts in the field, managers, governments of the world ...while disagreeing on almost everything all believe that the problem of production has been solved”*. Schumacher felt that humanity was tending towards a process of conquering nature and dominating it. In our endeavor for success, man has been going towards larger and bigger machinery than required and that this would be catastrophic if successful.

In order to capture the maximum economic benefit in the early stages of new product introduction, strategies including just-in-time, Kaizen, SMED, TQM, cellular manufacturing, lean, flexible and agile manufacturing are all aimed at supporting the delivery of more product on the market at lower cost and in a shorter period of time. The risk of obsolete plant and equipment is partially addressed by strategies such as reconfigurable and modular manufacturing systems.

Past efforts to introduce low-cost and appropriate technology, for instance to support local and regional employment and self-sufficiency, have not been successful with the rapid advance of manufacturing technology and associated improvements in productivity, quality and cost. Only recently have we been seeing models that incorporate the “other” costs of manufacturing in terms of the impact on society and environment (Dieren, 1995; Perman, 2003; Suter, 2003).

This research aims to develop a model that will allow the scalability of a given industrial process to be analysed and calculated. This model is designed to incorporate not only standard industry cost models but also socio-environmental costs as well as the many elements of manufacturing process design, some of which are inherently scalable and others that are not.

RECENT CASE STUDIES

There has been a trend in the last few decades in the steel, sugar and paper manufacturing industries to downscale using mini-mills. The availability of recycled material is spread uniformly throughout the industrialized world compared to raw materials. Recovering material from scrap can be a relatively low scale operation. In the past, manufacturers did not pursue this partly due to lack of technology. The effects of environmental pressures and awareness as well as increasing cost of raw materials have forced these industries to look for efficiency beyond “economies of scale” as appropriate technology became available. Historically, growth in industry was bought about by improvement in productivity through an increase in economies of scale; development efforts have almost always been “diverted almost entirely towards overcoming the technical obstacles limiting further size increases rather than towards innovative process alternatives” (Johansson & Holappa 2004).

The development of the electric arc furnace enabled the development of mini-mills in the steel industry. Furnace technology, ladle metallurgy and casting in sequence resulted in high productivity and efficiency and allowed for a high proportion of scrap to be recycled with high quality, relying less on the primary process from ore. A similar trend is found in the paper industry where large amounts of recycled pulp can be processed in mini-mills, again reducing the dependence on primary processes.

Research studies conducted on mini-mills using recycled paper instead of virgin pulp, have shown in pilot scale laboratory trials and theoretical calculations, that the mini-mill is expected to use less than half the electrical energy of current best available technology (350kWh per tonne of pulp), be thermal energy self-sufficient (a

fuel efficiency of 70%), recover more of the pulping chemicals (85-90%) and produce a eucalyptus pulp substitute from straw in 30-40 minutes, ready for bleaching. (Riddlestone, 2001).

Case studies conducted on mini sugar mills (McRobie, 1981) have focused on social and economic contribution. They noted that 40 mini sugar mills could be constructed at the expense of one large sugar plant. These mini plants would employ ten times more people and produce two and a half times more sugar. The social benefits far outweighed the cost savings achieved per tonne of sugar in large mills. On the other hand, a report produced by Business Line, India, (Viswanathan, 2004) was scathingly critical of the mini paper mills in India in the 1960s to mid-1980s as many closed down due to high operational costs, lack of proper effluent treatment and poor quality paper. Riddleston (2001) reported that the UK Government Department of Trade and Industry and industry itself developed technology between 1997- 2000 to produce pulp cleanly on a small-scale and in an economically efficient manner. The key feature of this mini-mill technology was a method of preparing straw to allow faster and more even pulping. This technology consisted of a re-designed twin screw extruder pulping system with increased throughput and reduced energy demand. Therefore, it seems evident that the poor performance of the Indian mini mills was more due to lack of technology than due to low scale operations.

A current case study being undertaken at UNSW involves the design of low cost robotic molding applications for boat manufacturing. Commercial robot applications for mold preparation are prohibitively expensive for small manufacturers. Automated mold manufacturing has been in practice with large manufacturers for some time and it gives them the ability to generate new models or variations of existing ones in short time periods. This competitive advantage was not enjoyed by smaller manufacturers. Due to substantial advances in actuation, sensing and control hardware and software, novel robot designs are being designed at a fraction of the cost of a standard industrial model. Other studies currently in progress include the downscaling of bio-diesel manufacturing processes, and winemaking.

KEY FACTORS OF MANUFACTURING SUCCESS (KFS)

Manufacturing processes need to possess a number of essential competencies in order to be commercially viable, similar to the Quality Function Deployment (QFD) concept of "order satisfying criteria" as a prerequisite for selling a product. These basic competencies are usually not explicitly stated but include the following:

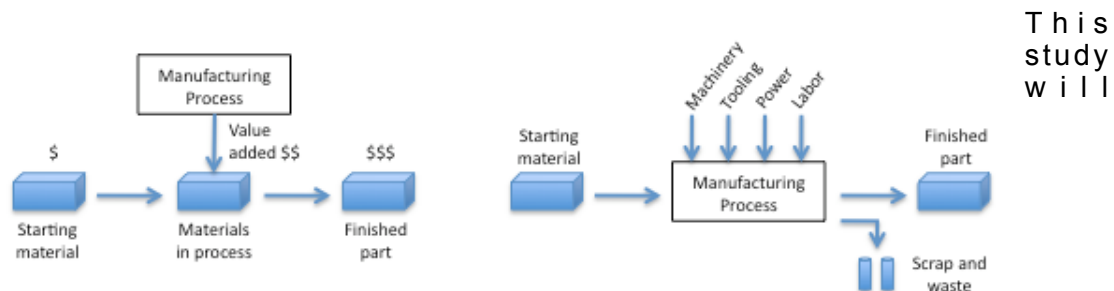
- **COST:** Profitability, return on investment (ROI)
 - **Resource efficiency:** Units of material, labour, energy (unit cost)
 - **Capital efficiency:** Investment, utilization, reliability (ROA)
 - **Productivity:** Cycle time, throughput, yield
- **QUALITY:** Market for product, minimization of waste
 - **Capability:** Process design, product-process alignment
 - **Control:** Process control, critical process variables
- **SUPPLY:** Ability to satisfy market demand
 - **Capacity:** Capacity unit, capacity flexibility, economic unit size
 - **Performance – OEE:** Availability, reliability, throughput, quality
- **RISK:** Minimize commercial and OHS&E risk
 - **Safety:** Process design
 - **Regulatory Compliance:** Applicable standards
 - **Environmental impact**
 - **Social impact**

In addition, and depending on the nature of the market and other external forces according to Porter's Model (Lovingsson & Ebooks 2005), manufacturing processes need to satisfy a number of other advanced competencies if the organisation wants to be successful in the long term. These advanced competencies focus on longer term, sustainability issues.

➤ **CONTINUOUS IMPROVEMENT and INNOVATION**

- **Cost:** Future cost-down ability
- **Quality:** Improved capability, markets become more demanding
- **Supply:** Reduced order lead time (Just-in-time), increased customization
- **Risk:** Strategic alignment of capital, process flexibility and understanding

There are additional competencies primarily associated with organizational, marketing and relationship management, but these have more to do with corporate organization and management and will therefore not be considered here. Many of the variables associated with the above mentioned process competencies are dynamic in nature and so change as a function of time. However, current benchmark data is indicative of the level of the basic competency required in real time and trend maps can be used to extrapolate competency performance in the future.



This
study
will

develop a methodology that is capable of identifying key scale and process design drivers in terms of these process competencies and incorporate dynamic trends to the model how these may change over time. The outcome is a scalability index that may be applied initially during the conceptual design stage and subsequently updated to adapt to new opportunities that may positively affect scalability. The next step in the formulation of such a methodology is the development of a cost model that can be universally applied to different types of processes. This is discussed next.

MANUFACTURING COST MODEL

In order to provide a link between the manufacturing KFS and process design drivers it is necessary to apply a manufacturing cost model and to demonstrate that the key cost drivers of a process are intimately linked with product and process design characteristics. In particular it is important to establish value added (VA) as an economic interpretation of the complexity of a manufacturing process and therefore process design. Kalpakjian & Schmid (2001) provide an economic and technical representation of a production process. This is shown in figure 1.

Figure 1: The manufacturing process as a (a) technical and (b) economic system (Kalpakjian & Schmid (2001)).

van Breukelen et al (2000), developed a more detailed cost model, useful as a basis for calculating VA and capital velocity (CV), a measure for calculating the efficiency of the use of capital resources. This cost model is shown in figure 2.

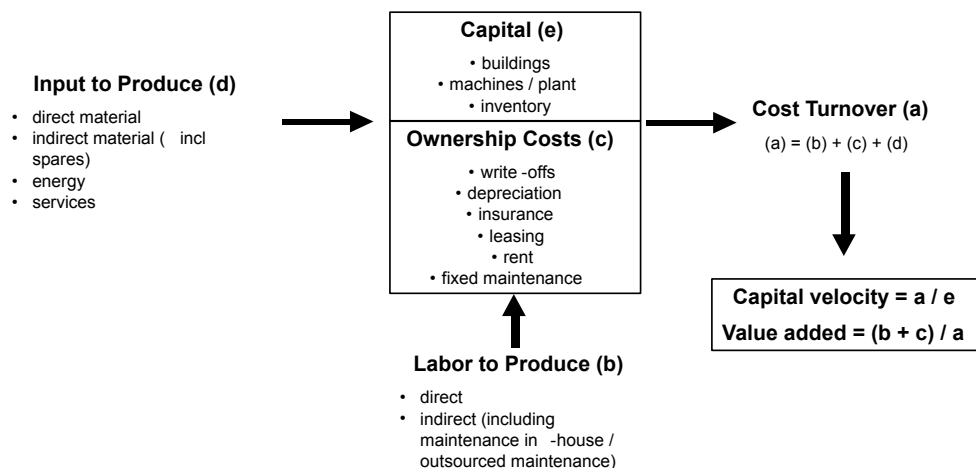


Figure 2: The manufacturing cost model and the basis for calculating value added (VA)

The total cost of product leaving the manufacturing system is equal to the sum of raw material costs entering the system, the labour costs contributed by the organisation and the cost of capital. Value added is the ratio between the costs that are contributed by the manufacturing process (labour and capital) divided by the total cost. Value added includes all costs added to the product, whether these costs are in fact “value adding” or “cost adding”.

The efficiency of the use of capital resources is given by the ratio of total cost and investment in capital, which in the case of manufacturing includes process plant and equipment, buildings, services and inventory. We give this ratio the name “capital velocity” because the velocity vector reflects two important characteristics, namely speed and direction. Speed is indicative of how efficiently capital is employed in the manufacturing system, whereas the direction of the velocity vector reflects how well the nature and capability of the asset base is aligned with the current and future direction of the manufacturing strategy associated with the system.

The study conducted by van Breukelen, Koolhaas et al. (2000) has established the presence of a strong relationship between capital velocity and value added for modern, automated manufacturing systems. These manufacturing systems incorporate automation technology to achieve the KFS drivers as opposed to a reliance on cheap manual labour. This is shown in figure 3. Implicit in the benchmarking data shown is the assumption that a certain level of productivity has been achieved such that the VA figures are not unnecessarily inflated with unproductive costs. Figure 4 illustrates the concept of the industry cost curve for product that is predominantly generic and where little differentiation exists between suppliers. The high-volume, low-cost producers “manage” supply and price. The

single shaded producer on the right (E) is only marginally profitable, whereas the producer on the far right (F) is unprofitable.

The significance of the relationship derived in Figure 3 is that for a given level of value added (read “process complexity” or “industry activity”) there is an optimum level of investment in capital assets. The premise of this argument is that regardless how desirable it may be to up or downscale a process, basic constraints such as the level of capital investment must be maintained in order to remain competitive, now and in the future.

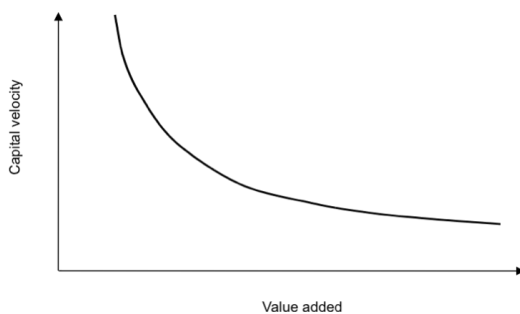


Figure 3: CV as a function of VA

(adapted from van Breukelen et al, 2000)

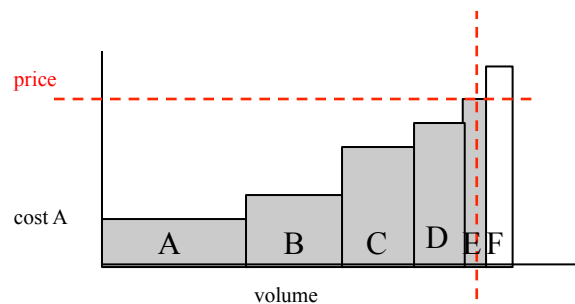


Figure 4: The industry cost curve concept

PROCESS DESIGN DRIVERS

For the purpose of establishing a basic set of process design drivers it is useful to further develop the abstract shown in Figure 1a. This is shown in Figure 5. This model is an abstract representation of a generic machine process and the factors that influence its design and performance.

A manufacturing process consists of a number of building blocks, including process equipment (machinery), associated automation and materials handling, a suitable layout and topography (e.g. a flexible manufacturing cell), and control software implemented at different levels within the process (device level, cell level, etc). The selection process for each of these building blocks depends on the volume of product to be manufactured and on the flexibility required. Flexibility is a process characteristic that reflects the ability of the process to absorb changes in design, quantity, product mix and so on, without undue economic penalty. This is shown graphically in Figure 6.

The essential **design drivers** can be summarized as follows:

- The product: its design, functionality and features translated into manufacturing steps and operations
- The level of value added (VA)
- The level of demand, and its projected growth
- Supply and service criteria
- The lifecycle of the product, and future design variations and trends
- Benchmark cost range for similar products offered by competitors.
 - An alternative to the benchmark cost is the estimated level of revenue less a gross margin (say 40%) divided by the annualized volume of production.
- Technical product and process knowledge required

- Cost of automation
 - Benchmarks cost indicators for actuators, sensors, controllers, computer hardware, software
- Cost of mechanical systems
 - Expressed on the basis of a “generic mix” of mechanical elements, \$/kg, \$/unit of output (structure, bearings, gearing, valves, etc)
- Cost of support services
- Labour cost (local and international)
 - For different skills required

The abovementioned drivers are “semi-dynamic” in the sense that they are not expected to remain constant over time. However they are not expected to behave in an entirely stochastic way either. Rather a forecasted trend line is associated with each of these variables and this trend line may be represented mathematically. An example of such a trend is the decreasing price of computer hardware. This is shown in Figure 7.

The **design decisions** include the following:

- Selection of manufacturing process and technology
- Required flexibility of the process
- Size or scale of the mechanical system
 - This can be expressed in terms of physical size, production throughput, the scale versus cost of the system.
- Materials handling and storage requirements
- The level of automation: the degree and extent of actuation, sensing and control
 - Within the process
 - External to the process
 - Grade of automation (short, medium or long term)
- Support services required, and their scale

In addition, the design decisions are subject to a number of constraints, including:

- Capital cost is constrained by the CV-VA equation
- Return on investment and payback time
- Automation and materials handling costs are included in the above constraint. As a rule, automation and materials handling contribute around 30-40% of total capital outlay.
- The unit production cost must be within, say $\pm 5\%$ of benchmark cost.
- Process reliability is an important consideration in terms of meeting demand and supply constraints and a suitable target could be, say 99%.
- Quality, again a target will be set in line with best practice and process capability
- Capacity must be greater than demand
- Value added constraint (depending on the market segment, product positioning, etc).

Since the aim of the study is to formulate a framework that is capable of assigning a “scalability index” to a process, each of these constraints will contribute to the index.

There are certain costs that are scalable and others that are not. An example of a cost that is scalable is the sheet stainless steel that is used in the manufacture of fermentation tanks in the wine industry. A smaller tank will contain less material and will therefore be cheaper (although the relationship may not be linear). Costs that are less scalable are the inlet and outlet valves fitted to these tanks as well as the

temperature sensors. Regardless of the size of the tank, these particular fittings are common. Part of the work involved in establishing the cost model is to identify the physical and mathematical extent of this scalability, and the factors that affect this. The cost model will be based on the model presented in Figure 2. with a detailed breakdown of the process into its basic building blocks and support functions as illustrated from the generic machine model in figure 5.

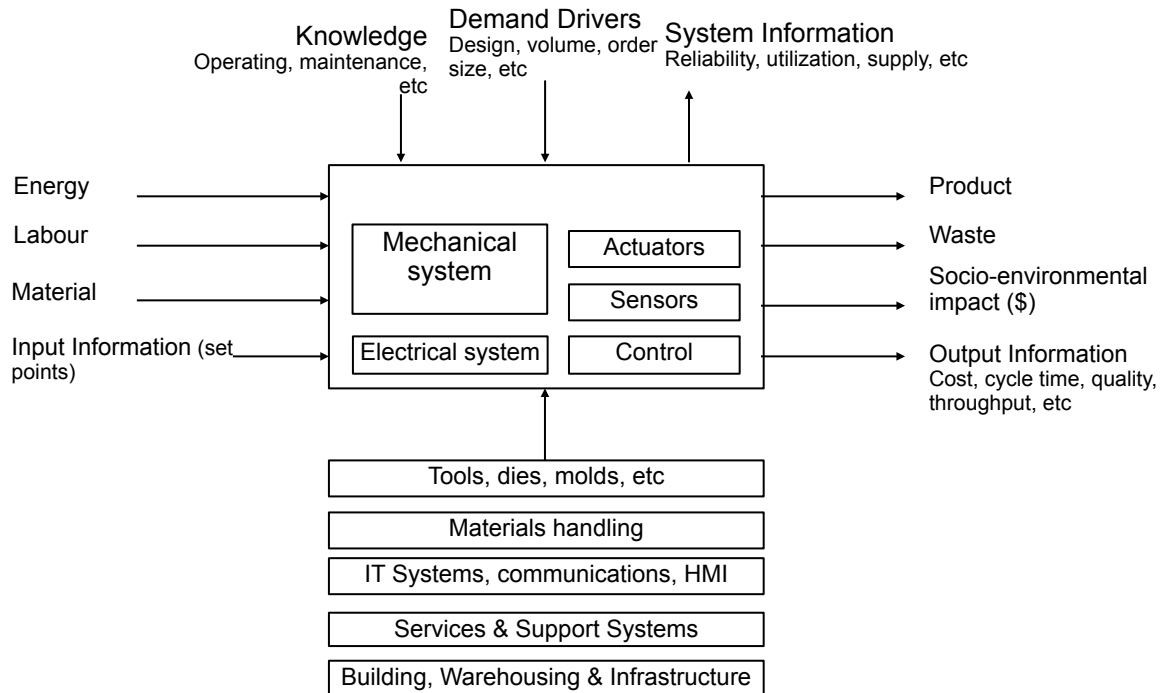


Figure 5: Abstract representation of an industrial machine.

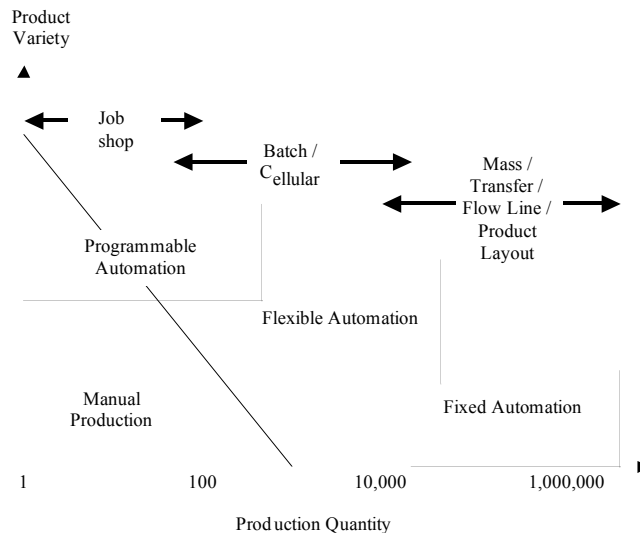


Figure 6: Manufacturing Automation as a function of Volume & Variety (adapted from Groover, 2001).

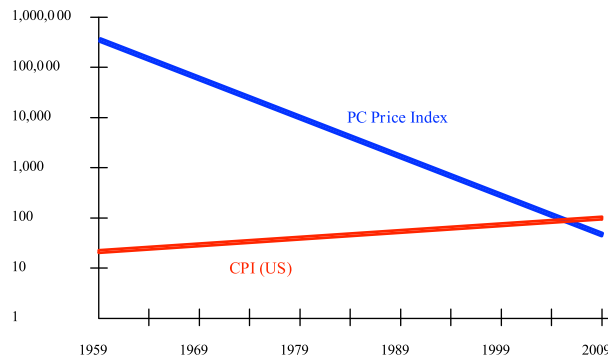
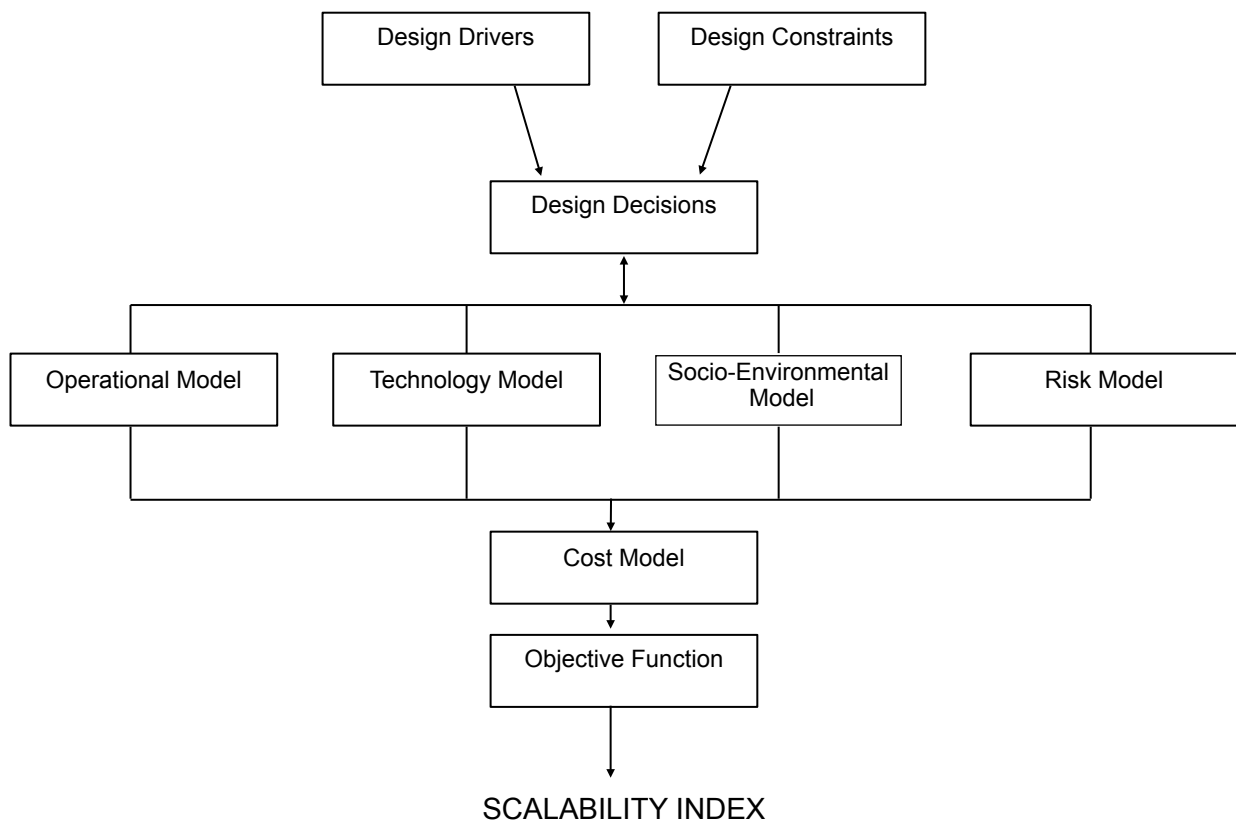


Figure 7: Historic trend for the cost of computing (Stiroh, 2007)

A SCALABILITY INDEX

The overall scalability model is shown in Figure 8. It incorporates the economic, technical, socio-economic, environmental and operational drivers and constraints discussed above.

Figure 8: Factors influencing Scalability



The model shown leads to a comprehensive evaluation of the issues that influence scalability, these being the operational, technological, socio-environmental and risk models, each evaluated in terms of cost and objective functionality. A more detailed

discussion of each model is beyond the scope of this paper, but will be presented at a later stage.

CONCLUSION

A high-level model for analyzing the scalability of machinery and industrial process has been proposed. It incorporates the key steps and activities that ensure that all relevant design drivers and constraints as well as costs and associated risks are considered in determining the extent to which a design may be successfully downscaled. Importantly, the model is based on the premise that even considering socio-environmental impact, the downscaled process must be economically viable in terms of cost (VA) and capital velocity (CV).

Having established this model, next steps will focus on analyzing the case studies mentioned earlier in order to continue to refine and validate this framework.

REFERENCES

- Dieren, W. v. (1995). Taking nature into account: a report to the Club of Rome : toward a sustainable national income. New York, Copernicus.
- Groover, M. P. (2001). Automation, production systems, and computer-integrated manufacturing, Prentice-Hall.
- Ishii, K. (2003). An economics for development and peace: with a particular focus on the thought of Ernst F. Schumacher, Springer.
- Johansson, A. and L. Holappa (2004). "From megaplants to mini-mills - a trend in steelmaking - a prospect for papermaking." Resources, Conservation and Recycling, 40,173-183.
- Kalpakjian, S. and Schmid S. R. (2001). Manufacturing engineering and technology, Prentice-Hall, New Jersey.
- Lovingsson, K. (2005). "The A-Z of Management Concepts and Models." from [http://info.library.unsw.edu.au/cgi-bin/local/access/access.cgi?url=http://www.unsw.eblib.com/EBLWeb/patron?target=patron&extendedid=P_309044_0&Online access](http://info.library.unsw.edu.au/cgi-bin/local/access/access.cgi?url=http://www.unsw.eblib.com/EBLWeb/patron?target=patron&extendedid=P_309044_0&Online%20access)
- McRobie, G. (1981). Small Is Possible. London WCI, Jonathan Cape Ltd.
- Perman, R. (2003). Natural resource and environmental economics. Harlow, England, Pearson Education.
- Riddlestone, S. (2001). Case Study: The MiniMill Concept. The Paper Industry Research Association (PIRA) Conference "Cost Effectively manufacturing Paper and Paperboard from Non-Wood Fibres and Crop Residues" Amsterdam, The Netherlands. .
- Schumacher, E. F. (1999). Small is beautiful: a study of economics as if people mattered. Point Roberts, Wash., Hartley & Marks Publishers.
- Suter, K. (2003). Making the Environment Count. Contemporary Review. **282**: 222-227.
- van Breukelen, Q. H., Koolhaas C.B and Kumpe, T, (2000). Benchmarken van industriële processen: resultaten van een wereldwijd onderzoek naar de operationele prestaties van industrieën, Uitgeverij Van Gorcum.
- Viswanathan, T. S. (2004). Mini paper mills fiasco. Business Line. Chennai, India, Financial Daily from The Hindu Group of Publications.

BIOGRAPHIES

Karthik Subramanian

Karthik Subramanian is a PhD student in the School of Mechanical and Manufacturing Engineering at the University of New South Wales. The topic of his thesis "Scalability of Manufacturing Process".

Dr John Olsen

Dr John Olsen served an apprenticeship as a fitter and machinist with Elcom Collieries, working at Newvale No 2, Newstan and Awaba Collieries. He later worked

as a fitter and machinist at both Newvale No 2 and Newstan Collieries. Dr Olsen completed a mechanical engineering certificate at Tighes Hill TAFE in 1988. He later completed a mechanical engineering degree (1st and Dean's Medal) at the University of Newcastle. Dr Olsen did a PhD on the 'Control of jet turbulence', completing in 2001. Dr Olsen has been a lecturer at the University of New South Wales since 2002. He has interests in thermodynamics, simulation and the production of biodiesel.

Dr Erik van Voorthuysen

Dr Erik van Voorthuysen conducts teaching and research in the fields of industrial robotics, automation, process control and data acquisition, reliability and life-cycle engineering, computer simulation and manufacturing management at the University of New South Wales. He has gained over twenty years experience in industry as a consultant with Cap Gemini and McKinsey & Co, and as founder and director of an engineering consultancy specializing in process control and asset management. He continues his work with industrial partners in robot design, process control and asset management. Recent research success includes an improved maintenance system for aircraft-engine overhaul resulting in significantly increased on-wing time. Current research focuses on small scale manufacturing and low cost robotic systems, both specifically aimed at SMEs.