International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713696255

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To cite this Article Spicer, P. , Yip-Hoi, D. and Koren, Y.(2005) 'Scalable reconfigurable equipment design principles', International Journal of Production Research, 43: 22, 4839 — 4852

To link to this Article: DOI: 10.1080/00268970500183042

URL: http://dx.doi.org/10.1080/00268970500183042

International Journal of Production Research,
Vol. 43, No. 22, 15 November 2005, 4839–4852

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Scalable reconfigurable equipment design principles

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(*Revision received May 2005*)

Scalability is one of six key characteristics found in reconfigurable manufacturing systems. Scalable systems satisfy changing capacity requirements efficiently through system reconfiguration, and in the flexible manufacturing literature this capability is called expansion flexibility. The development of modular scalable machine tools is a necessary precursor to achieving scalable systems. Unfortunately, there is little work describing the design of scalable machines. This paper establishes the need for scalable machines and a basis for evaluating and describing them. Applicable metrics are defined, and an architecture for scalable machines is presented. Two examples illustrate the scalable architecture. Finally, a design parameter based on a mathematical approach is presented to determine the optimal number of modules to be included on a modular scalable machine. This as a design parameter is important because it limits machine size and the number of module interfaces included in the base machine structure.

Keywords: Scalability; Reconfigurable manufacturing systems; Machine design

1. Introduction and literature review

High-volume manufacturing systems take months and even years to design and build. Because changes in economic conditions and demand outpace machine tool design, fabrication and completion, many manufacturers have difficulty purchasing capacity on an as-needed basis. One solution is to design scalable reconfigurable manufacturing systems (RMS) capable of efficiently adapting to changes in capacity requirements through system reconfiguration. This does not refer to speeding up and slowing down machines. Rather, this refers to rapid modifications in system and machine structures through the addition and removal of productive equipment modules. In the future, scalable systems will change the way managers approach capacity decisions by eliminating attempts to forecast economic conditions and by allowing managers to respond to market and demand fluctuations in minimal time. The end result will be reduced attributable overhead caused by unused capacity and greater flexibility to accommodate as-needed capacity increases.

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International Journal of Production Research
ISSN 0020–7543 print/ISSN 1366–588X online
http://www.tandf.co.uk/journals
DOI: 10.1080/00268970500183042

The development of modular scalable machine tools is necessary to achieve scalable systems, because modular machine tools facilitate rapid addition and removal of productive modules as required for scalability. Currently, uncertainty exists as to how such machines should be designed, because to date, there is little literature addressing this issue.

A basic concept of scalability in manufacturing systems is dated to the early 1980s (Browne *et al.* 1984, Sethi and Sethi 1990, Abdel-Malek and Wolf 1993). At that time the term for scalability was expansion flexibility and this original term is found in flexible machine systems (FMS) literature. According to Browne *et al.* (1984), Sethi and Sethi (1990) and Abdel-Malek and Wolf (1993), expansion flexibility references the capability to expand or contract production capacity of an FMS using a modular structure.

Several authors in FMS literature gave general recommendations for the design of manufacturing systems with expansion flexibility. A summary of recommendations found in FMS literature is given in Sethi and Sethi (1990); recommendations with implications on machine design include the following:

- Build small production units and expand by duplicating these small units.
- Provide an infrastructure to facilitate system growth.
- Design the system so it can be expanded without requiring significant new designs.

These recommendations exemplify general characteristics of scalable machine systems, but they neither establish nor are they intended to represent a comprehensive, systematic design approach to be applied to this emerging technology.

While scalability is known and understood in academic and industry-related literature (Hansen 1991, Nussbaum and Agarwai 1991) presents scalability as it pertains to computing and software development; and refers to the capability of computer systems to be readily expanded for increased capacity. Typically, this expansion employs parallel processing and modular hardware elements to facilitate expansion and the increase of capacity. Since the term scalability is so well known, the term is used instead of expansion flexibility in the domain of RMS.

Similarly described in RMS literature, scalability is listed as one of six key characteristics of reconfigurable manufacturing systems in Koren *et al.* (1999). The specific definition given for scalability in Koren *et al.* (1998) is 'the ability to adjust the production capacity of a system through system reconfiguration with minimal cost, in minimal time, over a large capacity range, at given capacity increments'.

References to scalable machine tools are found in RMS literature authored by Landers *et al.* (2001). Here, the concept of a reconfigurable machine tool (RMT) is introduced as a modular machine with a modular control system that gives manufacturers the ability to modify machine structure to suit specific manufacturing needs. Landers *et al.* focused on reconfiguration to address changes in product design; however, they also provide an example of a modular (scalable) machine that can be reconfigured to decrease cycle time, therefore increasing the productivity of the machine.

In Katz *et al.* (2002) and Koren and Katz (2003), the concept of an RMT is extended beyond processing equipment to inspection equipment, and the reconfigurable inspection machine (RIM) is introduced as an inspection machine with a modular reconfigurable structure. The authors emphasize the machine's ability to adapt to inspect different products. The RIM, however, is also scalable. For example, by adding productive modules, which in this case are inspection sensors, the inspection rate can be increased. This demonstrates how scalable machines are not limited to metal cutting machines and how challenges of scalable machine design also apply to inspection and general processing equipment.

Spicer *et al*. (2002) introduced the concept of a machine tool designed specifically for scalability. It is called a multi-spindle scalable machine tool. This concept provides the option of adding and removing multiple spindles on an as-needed basis. The benefits of this concept include: reduced capital investment, reduced reconfiguration time, and reduced consumption of space. However, no detailed design approach was provided to design such a machine or to develop similar concepts for other manufacturing applications.

Based on previous literature, scalable machines are important for realizing scalable systems, unfortunately it is not fully understood how they should be designed. The purpose of this work is to establish an understanding of scalable machines by presenting parameters for their design along with examples of features that provide both economic and productivity related benefits. To begin, existing machines are examined to demonstrate the need for a new class of modular scalable machines. Then a general classification framework for modular machines is presented and followed by the description of the preferred architecture for scalable machines. Next, two scalable machine concepts are offered to illustrate the preferred architecture, and finally, a mathematical approach is described to determine the optimal number of modules to be placed on a scalable machine.

2. Review of existing machine tools

Ideally, scalable machines should be engineered and installed in small-capacity increments, purchased and set-up with short lead-times, have a low cost per unit of capacity, and require a small amount of floor space per unit of capacity. These attributes ensure scalable systems will effectively respond to market fluctuations causing changes in demand for capacity in an economically viable way, while simultaneously occupying the minimum floor space and maintaining higher production volumes. Therefore, to understand a machine's effect on scalability, it is important to assess machines on the basis of four key metrics: capacity increment size, lead-time, cost per unit of capacity and floor space per unit of capacity.

This section focuses on machine tools used for high-volume machining to illustrate the need for scalable equipment and to clarify the basis for evaluating scalability. Currently, manufacturers must choose among four general types of machine tools for high-volume machining systems. These choices include: single-spindle computer numerical control (CNC) machines (figure 1(a)); dedicated transfer machines (figure 1(b)); head changers (figure 1(c)); and multi-spindle CNC machines (figure 1(d)). Each option has a unique effect on system scalability.

Typically, CNC machines (figure 1(a)) are designed to be flexible standardized machines with one cutting spindle having programmable motion in three or more degrees of freedom. While the CNC structure is flexible and capable of producing a variety of different parts, it is inefficient in terms of floor space per unit of capacity and cost per unit of capacity, because three or more motion units are required for

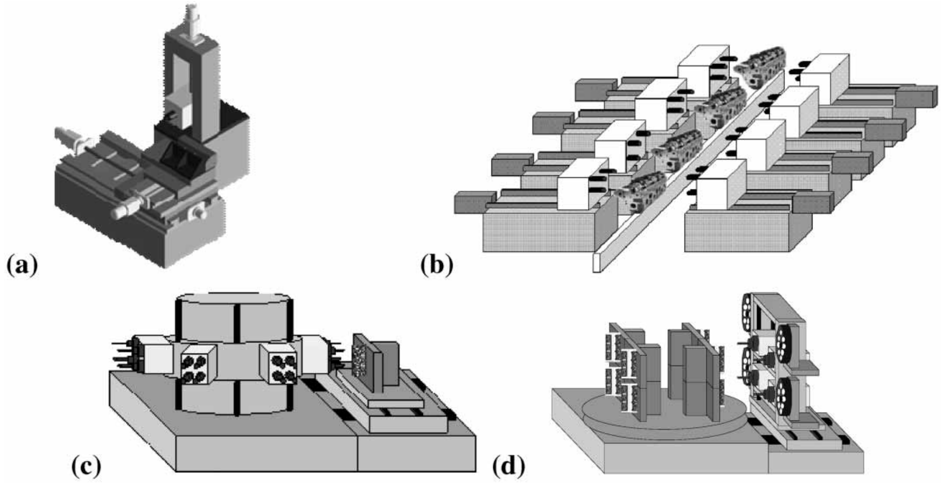

Figure 1. Four major machine tool options: (a) single-spindle CNC machine, (b) dedicated transfer machine, (c) head changer and (d) multi-spindle CNC machine.

each spindle, and because CNC machines cost 1.3–1.5 times more than dedicated transfer systems (Aronson 1998). However, since each machine has one cutting spindle, CNC machining centres can be installed in small-capacity increments; and because they are standardized, the lead-time to purchase and deliver CNC machines is short. Therefore, CNCs perform well with respect to half of the four stated metrics, but fall short of being truly scalable due to a disproportionate consumption of floor space and high cost per unit of capacity.

In contrast to the flexibility of a CNC machine, a transfer machine (figure 1(b)) is designed to produce one specific part efficiently. A transfer machine is comprised of several stations linked by a transfer mechanism for material handling (e.g. transfer bar). These stations simultaneously operate on a quantity of parts progressing sequentially from one station to the next with each station completing a task or tasks that represent various stages of production. Parts are completed after passing through all the transfer machine's stations; and a finished part is produced with each index of the transfer mechanism. Typically, each station has one axis of motion along with a multi-spindle head, and the multi-spindle head has several cutting spindles, cutting in unison.

Transfer machines have a low cost and small space usage per unit of capacity because several cutting spindles are used for each axis of motion. However, lead-times associated with the design and manufacture of transfer machines are greater because an entire system must be engineered for each part variation. Lastly, transfer machines have a large capacity increment size because they have a complex structure comprised of several productive stations joined together. In terms of scalability, CNC machines fall short because the cost per unit of capacity is too high and because the floor space per unit of capacity is too great. Conversely, transfer machines have a lower cost per unit of capacity and require less floor space per unit of capacity than CNC machining centres; however, like CNC machining centres, transfer machines perform well with respect to only two of the four stated metrics.

The third option is to use head changers (figure 1(c)). Head changers combine the productivity of multi-spindle drill heads with the flexibility of CNC machines. The basic concept of a head changer is a multi-axes CNC machining centre using multi-spindle drill heads instead of a single-spindle for cutting. This allows the machine to drill several holes at once while simultaneously reducing the number of tool changes and, consequently, cycle time. This capability makes head-changers more productive than single-spindle CNC machines. However, they are less productive than transfer machines because only one multi-spindle head is used at any given time. When not in use, idle multi-spindle heads are stored on a carrousel. Comparatively, head changers have a capacity increment larger than CNCs, but smaller than transfer machines. For the same reasons, the cost and floor space usage per unit of capacity is also between a CNC and a transfer machine. Finally, since their structure consists of a standardized CNC machine with custom-built multi-spindle heads, the lead-time is longer than a traditional CNC; however, because the machine is standardized, with the exception of the multi-spindle heads, the lead-time for this concept is shorter than that of a transfer machine.

The final option is to use multi-spindle machining centres (figure 1(d)). These machines employ multiple spindles in a different way than head changers. Like head changers, the basic structure is a multi-axis CNC. However, two or more spindles are permanently attached to the machine column. These spindles are similar in design to those used on a standard single-spindle CNC. For example, each spindle has automatic tool change capability. In addition, the spacing of the spindles is such that they can machine an identical feature on two or more parts at the same time. Therefore, excluding tool changes and head change time, the production rate of a (n) spindle multi-spindle CNC is similar to a head changer with an average of (n) spindles per head.

Comparing differences between multi-spindle CNCs and head-changers, there is a shorter lead-time for the former because spindles are standardized while the latter requires all spindles employed to be of a custom design. Overall, the scalability performance of a multi-spindle CNC is somewhat better than a head-changer.

Table 1 summarizes a comparison among the four types of machines. None of the machines is truly scalable. Each machine type is limited in one way or another. The logical solution is to develop modular machines that can be purchased in small-capacity increments and with shorter lead-times. These machines must also be efficient producers so cost per unit of capacity and use of floor space per unit of capacity are minimized at high production volumes. For example, one may conceive a modular transfer machine that can be installed in fractional amounts, yet performs as efficiently as a transfer machine at higher volumes.

Table 1. Machine scalability comparison.

Machine type	Capacity increment	Lead time	Cost per unit of capacity	Floor space per unit of capacity
Single-spindle CNC	Small	Small	Large	Large
Transfer machine	Large	Large	Small	Small
Head changer	Medium	Medium	Medium	Medium
Multi-spindle CNC	Medium	Small	Medium	Medium

Increasingly, machine tool builders are building from a set of standard modules. This is a promising trend and a step in the right direction. However, the machines built today are not easily reconfigured at the manufacturing plant. Therefore, there is little or no possibility of an end-user incrementally increasing capacity. This drawback is demonstrative of the need to develop principles for designing truly scalable machine tools that can be easily reconfigured at their point of use.

3. Scalable machine tool architecture

With modular machines, equipment modules can be added to a base machine structure and later removed, rearranged or replaced as required. The structure of a generalized modular machine is represented by figure 2(a). In the centre of figure 2(a) is the machine base. Proceeding from the base are the machine modules represented by circles with the letter 'M'. The various font types represent different kinds of modules and the empty circles represent spaces where modules may be connected in the future.

In order to keep the notion of a modular machine from exploding in complexity, boundaries are placed on the architecture by defining three basic parameters concerning machine architecture: module levels, module types and module positions.

Module levels are serial connections of modules. For example, three levels of modules are shown in figure 2(a). The first level consists of modules attached to the machine base; second-level modules are attached to first-level modules, and so on. In general, it is possible to have any number of levels of modules; and having more module levels improves the machine's ability to change for different product designs. On the other hand, additional module levels are not likely to improve the scalability of a machine. The first level of modules has the greatest impact on scalability. Therefore, the work in this paper is restricted to single-level machines.

The second important architectural parameter is a measure of the number of unique module designs allowed on a machine. For example, figure 2(a) shows six different module types. Conceivably, a machine may have several different module types adding functionality as well as complexity. Again, the benefit gained by having

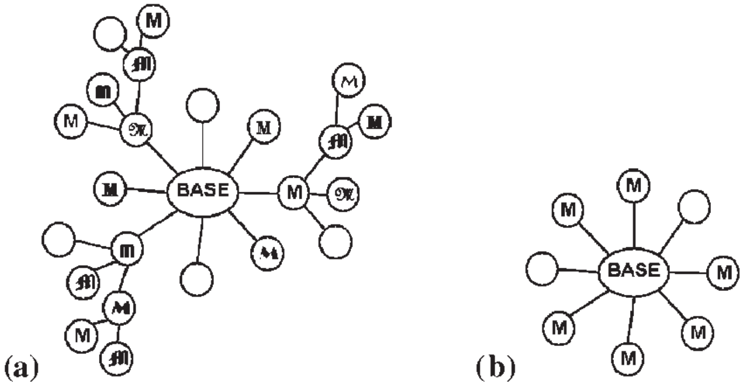

Figure 2. Machine tool architectures: (a) general machine tool and (b) scalable machine tool.

more module types is the greater possibility of adapting the machine to different product designs. However, a single module type may be adequate for scalability, when the issue to be addressed is production rate. Hence, machines with a single module type are discussed in this paper.

The final parameter is the number of available module positions on the machine. These module positions are locations designed to accept a module. For example, figure 2(a) shows 23 positions, with five unused positions. For scalability, the number of module positions has the most obvious impact. If designed properly, a scalable machine will increase in capacity (e.g. production rate) with each additional module. Hence, a machine with more module positions will have a better capability to scale up in capacity. Ideally, scalable machines will include just enough module positions to facilitate the necessary changes in capacity without significantly reducing machine reliability or increasing planned maintenance.

Given the above discussion, the most logical starting point for understanding scalable machines is with a single module level, single module type and n module position architecture (i.e. $1/1/n$). This means all modular machines with a single module level and single module type will fit into this architecture regardless of the number of module positions (n). Figure 2(b) illustrates the ($1/1/n$) architecture, which is the focus of the remainder of this paper and will be referred to henceforth as the scalable machine tool architecture.

4. Two scalable machine tool examples

This section illustrates how machines may be designed according to the ($1/1/n$) scalable architecture. Continuing with the illustrations given above, two machine concepts from the high-volume machining domain are offered as examples. Neither concept exists today in industry, but both concepts are based on existing machine tool technology. The first concept is based on the multi-spindle CNC architecture and is therefore called a scalable multi-spindle CNC machine (SMS-CNC). The second is a combination of a CNC machine, transfer machine and a conveyor loop and is therefore referred to as a scalable loop transfer machine (SL-Transfer).

4.1 *Scalable multi-spindle CNC (SMS-CNC)*

Figure 3 shows a four-spindle SMS-CNC. This concept was first described in Spicer *et al.* (2002). This machine can be reconfigured, enabling it to take on four different states ($n = 4$). In each state, it has a different production capacity. The machine scales by adding (or subtracting) spindles, tool changers and part fixtures. In this case, a module is defined as a set of one spindle, one tool changer and two part fixtures. With each additional module, the production rate increases as if another whole single-spindle CNC were purchased. Therefore, the capacity increment of an SMS-CNC is equivalent to the capacity increment of a single-spindle CNC.

Because the SMS-CNC is constructed from standard and identical modules, the cost of the SMS-CNC increases linearly with the number of spindles. With each additional module, the machine incurs the cost of a spindle, tool changer and

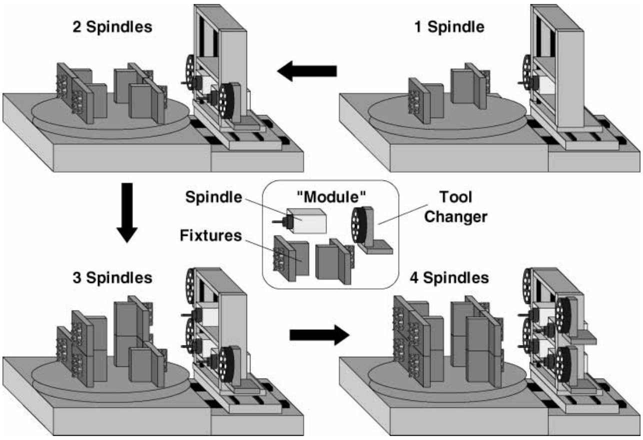

Figure 3. Four-spindle SMS-CNC.

Table 2. Scalability comparison: new concepts.

Machine type	Capacity increment	Lead time	Cost per unit of capacity	Floor space per unit of capacity
SMS-CNC	Small	Small	Medium	Medium
SL-Transfer	Medium	Medium	Small	Small

a pair of two part fixtures. Therefore, the *n*-spindle machine cost (K_n) is a function of the base machine cost (C_B) and module cost (C_M):

$$K_n = C_B + (n)C_M. \tag{1}$$

Overall, the SMS-CNC should have improved scalability performance over a multi-spindle CNC (table 2). It should have a small-capacity increment equivalent to a single-spindle CNC. It should also have a short lead-time since it has a standard design with standardized modules. Lastly, its performance should be similar to a multi-spindle CNC with regards to cost and floor space per unit of capacity. This should be an improvement over a multi-spindle CNC. However, there is still opportunity for improvement with regards to cost and floor space.

4.2 *Scalable loop transfer machine (SL-Transfer)*

Another scalable machine concept, the SL-Transfer machine, is shown in figure 4. The machine is shown with four part carriers and eight workstations. The number of part carriers and workstations may vary depending on the application. The part carriers can be considered as modules. Each module has its own two-axis (x and z) CNC motion capability and a part fixture. Each workstation has a stationary multi-spindle head that performs a unique set of machining tasks. The part carriers drive themselves in the x direction with CNC motion along linear slide-ways to each workstation. The carriers use their z-axis for feed motion into the multi-spindle heads. After the carriers travel to each station in series, they loop back to the beginning and start over with another part.

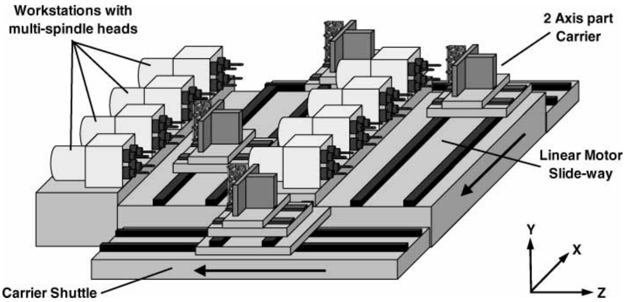

Figure 4. Scalable loop transfer machine (SL-Transfer).

For scalability, the SL-Transfer scales by adding (or subtracting) part carrier modules. With one part carrier, the processing time per part is the round-trip time of the part carrier. The round trip time includes the time to load/unload parts, the processing time at each workstation, the travel time between stations, and the time to shuttle between the front slide-way and the rear slide-way.

The inverse of the round trip time (RTT) is the capacity increment (CI) of the SL-Transfer machine. This is given in equation (2). It should be similar to a head changer's capacity increment:

$$\mathrm{CI} = \frac{1}{(\mathrm{RTT})}. \tag{2}$$

With each new carrier, another part can be processed simultaneously on the machine. Therefore, the production rate (P_n) of the system with n pallets is:

$$P_n = \frac{n}{(\mathrm{RTT})}. \tag{3}$$

But there is a limit to this production rate. The production rate, given by equation (4), is eventually limited by the processing time (T_{WMAX}) at the slowest workstation on the machine. This can be a workstation, the part shuttle mechanism or the part loading/unloading station:

$$P_{\mathrm{MAX}} = \left(\frac{1}{T_{\mathrm{WMAX}}}\right). \tag{4}$$

The maximum production rate places a limit on the maximum number of modules (N_{MAX}) added to the machine. Equation (5) can be used to compute N_{MAX} for an SL-Transfer machine:

$$N_{\mathrm{MAX}} = \left\lfloor \frac{\mathrm{RTT}}{T_{\mathrm{WMAX}}} \right\rfloor. \tag{5}$$

Just like the SMS-CNC, the cost of the SL-Transfer increases linearly with the number of part carriers. When each new part carrier module is added, the machine incurs the cost of a part fixture and the cost of two axes of motion. Again, the cost of the part fixture and two axes of motion can be grouped together and called the module cost (C_{M}). The part carrier module costs (C_{M}) are then added to the cost of the base machine (C_B) to determine the n-carrier machine cost (K_n). This is the same as equation (1).

Overall, the SL-Transfer has several advantages. First, its structure is compact and highly productive like a transfer machine, so it should have a small cost and floor space usage per unit of capacity. In addition, its modularity should give this machine a smaller capacity increment (similar to a head changer). Lastly, the lead-time for this concept is likely to be smaller than a transfer machine. This is because machine bases and part carriers are standardized. Only the multi-spindle heads are customized. Therefore, its initial lead-time should be similar to a head changer. However, its lead-time for additional capacity (additional part carriers) will be small due to their standardization. The comparison in scalability performance between the SMS-CNC and the SL-Transfer is shown in table 2. Notice that both should be improvements over existing machine concepts, but there is still opportunity for improved concepts.

5. Optimal number of modules

The maximum number of module positions allowed on a scalable machine is a key design parameter. On one hand, it is advantageous to design the machine to hold many modules. This is because the cost of adding modules should be less than starting again with another machine base. However, with more electrical and mechanical hardware on the machine, there is an increased likelihood of machine failures. The result is the machine's availability, and therefore its productivity gains, become smaller with each additional module. This creates a trade-off between the productivity advantages of additional modules and productivity losses due to decreased availability. This trade-off suggests an optimal number of module positions to be included on a scalable machine tool. If more capacity is needed beyond that point, a second machine should be built.

5.1 *Quantitative analysis*

To determine the cost-optimal number of module positions (n^*), one must determine when the ratio of machine production rate to cost (i.e. production rate per unit cost) no longer increases with additional modules. To begin the analysis, the equations governing machine production rate are described.

Equation (6) gives the production rate of a scalable machine excluding machine failures:

$$P_n = (n)(P_M) \tag{6}$$

where P_M is the production rate of a module and P_n is the machine production rate as a function of n.

Equation (7) quantifies the effect of additional modules on overall machine availability:

$$A_{\text{Machine}} = (A_B)(A_M)^n \tag{7}$$

Table 3. Machine availability comparison.

n	A_{Machine} ($A_{\mathrm{B}}=0.99 A_{\mathrm{M}}=0.99$)	A_{Machine} ($A_{\mathrm{B}}=0.99 A_{\mathrm{M}}=0.97$)	A_{Machine} ($A_{\mathrm{B}}=0.99 A_{\mathrm{M}}=0.95$)	A_{Machine} ($A_{\mathrm{B}}=0.99 A_{\mathrm{M}}=0.90$)
1	0.9801	0.9603	0.9405	0.8910
2	0.9703	0.9315	0.8935	0.8019
3	0.9606	0.9035	0.8488	0.7217
4	0.9510	0.8764	0.8064	0.6495
5	0.9415	0.8501	0.7661	0.5846

where n is the number of modules, A_{M} is the probability a module is available to run and A_{B} is the probability that the base machine is available to run. The result is the probability (A_{Machine}) the machine is available to run.

Table 3 shows how the availability of a scalable machine decreases with various module availability assumptions. The data show the availability with several modules may drop significantly.

After combining equations (6) and (7), equation (8) is obtained. This is the production rate of the machine adjusted for availability:

$$P_n = (n)(P_{\mathrm{M}})(A_{\mathrm{B}})(A_{\mathrm{M}})^n \tag{8}$$

where P_{M} is the production rate of a module.

In all practical cases (i.e. when $n > 0$ and $A_{\mathrm{M}} < 1$), the production rate function given in equation (8) has a single maximum. This means one can determine the number of modules that offer the maximum production rate ($n_{\max}$). This is done by differentiating P_n with respect to n, setting it equal to zero, and solving for $n_{\max}$. Equation (9) is the derivative ($\mathrm{d}P/\mathrm{d}n$):

$$\frac{\mathrm{d}P}{\mathrm{d}n} = A_{\mathrm{B}} P_{\mathrm{M}} (A_{\mathrm{M}})^n [(n)\ln(A_{\mathrm{M}}) + 1]. \tag{9}$$

After setting ($\mathrm{d}P/\mathrm{d}n$) equal to zero and solving for $n_{\max}$, equation (10) is obtained:

$$n_{\max} = \frac{-1}{\ln(A_{\mathrm{M}})}. \tag{10}$$

Equation (10) is an important result because it gives the exact point when additional modules will no longer increase the production rate of the machine. However, this is not necessarily the cost-optimal number of module positions that should be available on a scalable machine. In fact, the cost-optimal number will be fewer. To determine the cost-optimal number of modules, one must determine when the production rate per unit cost of a scalable machine is maximized. After that point, a new machine should be built.

To proceed with the cost-optimal solution, one must recall the scalable machine cost equation given by equation (11):

$$K_n = C_{\mathrm{B}} + (n) C_{\mathrm{M}} \tag{11}$$

where C_{B} is the cost of the base machine, C_{M} is the cost of a module and K_n is the cost of the machine.

Table 4. Example machine characteristics.

Cost of the base machine	US$200 000
Cost per module	US$500 00
Availability of the base machine	0.95
Availability of a module	0.90
Production rate per module	100 units/day

If P_n is divided by K_n, the production rate per unit of cost of a machine with n modules is obtained:

$$G_n = \frac{P_n}{K_n} = \frac{(n)(P_{\mathrm{M}})(A_{\mathrm{B}})(A_{\mathrm{M}})^n}{C_{\mathrm{B}} + (n)C_{\mathrm{M}}}. \tag{12}$$

The optimum number of modules (n^*) will occur when G_n is at a maximum. Therefore, n^* can be solved by differentiating G_n with respect to n and setting it equal to zero:

$$\frac{\mathrm{d}G}{\mathrm{d}n} = \left(\frac{A_{\mathrm{B}}P_{\mathrm{M}}(A_{\mathrm{M}})^n[(C_{\mathrm{M}}(n) + C_{\mathrm{B}})(n)\ln(A_{\mathrm{M}}) + C_{\mathrm{B}}]}{(C_{\mathrm{M}}(n) + C_{\mathrm{B}})^2}\right). \tag{13}$$

After setting equation (13) equal to zero, the following quadratic equation is obtained:

$$C_{\mathrm{M}}(n^*)^2 + C_{\mathrm{B}}(n^*) + \frac{C_{\mathrm{B}}}{\ln(A_{\mathrm{M}})} = 0. \tag{14}$$

Finally, n^* is obtained by solving equation (15):

$$n^* = \left\lfloor \frac{-C_{\mathrm{B}} \pm \sqrt{C_{\mathrm{B}}^2 - 4C_{\mathrm{M}}(C_{\mathrm{B}}/\ln(A_{\mathrm{M}}))}}{2C_{\mathrm{M}}} \right\rfloor. \tag{15}$$

The optimal number of module positions (n^*) must be an integer and ≥ 1. So one must choose the positive root of the solution and truncate it to the next lowest value of n^*.

5.2 *Numerical example*

A numerical example is now offered to give a clearer understanding of this optimization. Assume that one is trying to determine the optimal number of module positions on a scalable machine tool with the characteristics given in table 4.

Using equations (8) and (12), one can plot the production rate of the machine (P_n) and the production rate per unit of cost (G_n). The plots are shown in figure 5.

Notice how the marginal production benefit of a module becomes smaller due to the effect of increased downtime. In fact, from equation (10), the machine production rate decreases beyond nine modules. At first, one may argue that it is beneficial to add up to nine modules to the machine, because the production rate increases up until that point. However, if equation (15) is used to take into account the amount of capacity gained with respect to the cost, the optimal solution is to design the machine with four module positions (figure 5(b)).

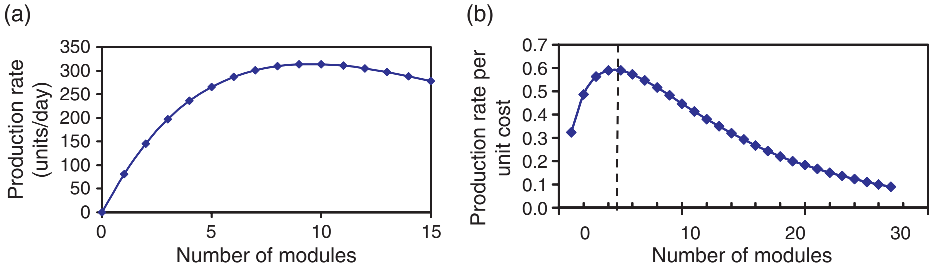

Figure 5. Example plots: (a) production rate versus number of modules and (b) production rate per unit of cost.

6. Conclusions

This work has illustrated the need for scalable machines and established a basis for evaluating and describing them. Two specific examples of such machines have been described, and a mathematical approach to aid in their design has been presented. With regards to evaluating scalable machines, four metrics have been defined: capacity increment size, lead-time, cost per unit of capacity and floor space per unit of capacity. An examination of current machine designs based on these metrics identified a need for more scalable machines. To address the need for scalability, a modular architecture of scalable machines has been proposed. With this architecture, incremental investments in capacity can be made by purchasing additional machine modules. This will offer the advantage of smaller capacity increments and shorter lead-times. If this architecture is applied to efficient machine designs, scalability can be improved.

Two concepts of scalable machines have been described that conform to the scalable machine architecture: scalable multi-spindle CNC (SMS-CNC) and scalable loop transfer machine (SL-Transfer). A qualitative evaluation based on the four scalability metrics suggests both concepts will have improved scalability performance in comparison with existing machines. However, there is an opportunity for even further improvement.

As a first step in the development of quantitative design methodologies for scalable machines, a mathematical approach has been developed to determine the optimal number of module positions (n^*) on a single-level, single-type, $(1/1/n)$ scalable machine. This is a cost-optimal solution, taking into account the machine investment cost, production rate and equipment availability as a function of the number of modules on the machine. The solution is quite useful because it is the key design parameter in a $(1/1/n)$ machine. It is also an analysis generally applicable to production equipment as well as inspection equipment. With this information, the maximum size of a scalable machine is determined along with the number of module interfaces to be included in the base machine structure.

Future work on scalable machines should proceed in three different areas. The first area is to expand the analysis of the $(1/1/n)$ architecture to more generalized architectures. For example, the most logical step is to consider cases with more than one module type. After that, multiple module levels may be considered.

The second area requiring research is the development of principles for scalable machine concepts. Such principles are necessary for determining how a machine should be partitioned into modules for optimal scalability with respect to the production of a certain family of parts. The application of these principles should, for example, succeed in identifying machine concepts that out perform the SL-Transfer and SMS-CNC.

Finally, the third area of future work should be to expand the research into different manufacturing process domains. Thus far, this work has focused on high volume machining systems. However, scalable design principles should be general enough so they can be adapted to other processes such as welding or assembly. For example, as long as one can envision machines performing other processes with a scalable architecture (i.e. $1/1/n$), the mathematical model developed in this work will apply.

Acknowledgements

The authors gratefully acknowledge the financial support of the Engineering Research Center for Reconfigurable Manufacturing Systems (NSF Grant EEC95-92125), University of Michigan, and the valuable input from the centres industrial sponsors.

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