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Scalability in manufacturing systems design and operation: State-of-the-art and future developments roadmap

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ABSTRACT

The paper covers the main design, management and operational aspects of scalability in manufacturing systems (MS). It promotes scalability as an area of research of MS theory and practice in order to enhance techniques and methodologies in existing MS paradigms using advanced and emerging design and management approaches and ICT, and meet challenges of emerging MS paradigms and support their promotion and effective and efficient deployment in practice. The paper presents an introduction to scalability, state-of-the art in manufacturing and computer science, and related applications including manufacturing and education and a roadmap for future research and developments.

1. Introduction

1.1. Objectives

Scalability of systems, and in our particular case of manufacturing systems (MS), could be seen as a system's feature that might provide a significant increase of potentials for resolving a number of problems in manufacturing systems design and operation and for enabling new visions, whether quantitatively or qualitatively. In other words, manufacturing systems scalability might provide further optimization of the manufacturing systems design and operation or to enable development of new manufacturing systems paradigms, for the sustainability and wellbeing society. Besides the functional aspects of scalability, which could be seen as primarily technical issues, considering a wider social concerns the scalability feature might also be seen as an instrument for increasing value (following requests for value creation and sustainable society, see [190]).

Thus, the specific objectives of the paper could be defined along the three main lines of scalability research, development and implementation. These are to:

1. incentivize exploration of "scalability" seeing it as the new potential, the new capacity, the new resource within "*classical*", or "*actual*" MS paradigm;
2. incentivize exploration of "scalability" seeing it as the new potential, the new capacity, the new resource for, and in, "*emergent*" MS paradigms; and
3. provide transfer of knowledge and ideas from other engineering and management areas, in which "scalability" is also explored, to manufacturing, This is especially relevant for the area of Computer Science[1] (or Computing Science, abbr. CS or CompSci).

1.2. Relevance I

The relevance of scalability might initially be evaluated indirectly through the references to scalability by the R&D community, under assumption that the R&D community reflects well the societal (including industry) requirements.

The analysis of the most important publication sources as well as of the most significant international and national openly published R&D Programs and Roadmaps show that the issue of "scalability", by the criteria of number of the papers that cite the term "scalability", or number of occurrences of the term "scalability" and as the topic in R&D Programs and Roadmaps, in the context of manufacturing, has in the last years seen steady growth.

On the other hand, the same analysis shows that "scalability" within the manufacturing community has started to gain major attention only since approximately the year 2000. This fact justifies that the relevance at this moment could be evaluated primarily through the references by the R&D community rather than by industrial applications, considering the "incubation" period needed for transfer of knowledge and technology to industry.

[1] 'Computer Science' denotation is adopted to refer to the entire area of computer based applications. Other terms are in use as synonyms, or may be used interchangeably, e.g. Informatics, Information and Communication Technologies (ICT). For the taxonomy of the Computer Science, see e.g. ACM Taxonomy at http://www.computer.org/portal/web/publications/acmtaxonomy and at http://dl.acm.org/ccs_flat.cfm.

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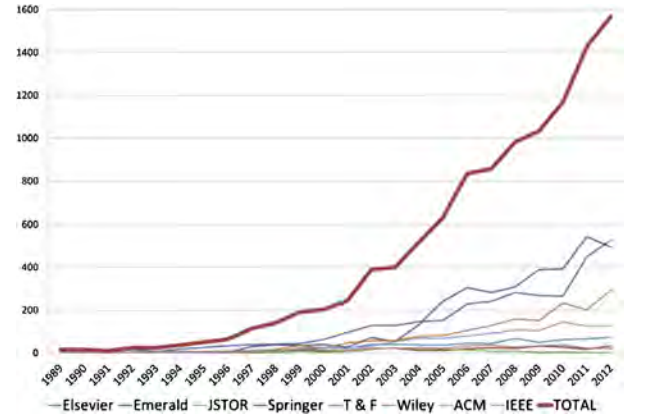


Fig. 1. Number of papers by the search terms '*scalability* AND *manufacturing*' in world leading publishers' collections.

Thus, the number of papers in collections of world leading publishers (Elsevier, Springer, T&F, Wiley, Emerald, JSTOR, ACM, IEEE) per year, in which the term "scalability AND manufacturing" occur is given in Fig. 1.

Concerning the CIRP community, the number of papers per year in CIRP Journals, i.e. "*CIRP Annals: Manufacturing Technology*" and "*CIRP Journal of Manufacturing Science and Technology*" where the terms "scalability" or "scalable" occur, is given in Fig. 2.

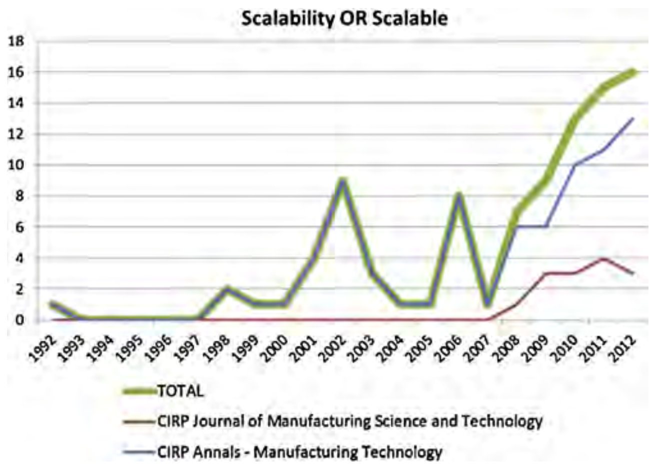


Fig. 2. Number of papers by the search term '*scalability*' in CIRP's journals.

In international and national Research & Development (R&D) Programs and Roadmaps, the occurrences of the topic and term 'scalability' could be assessed as regular, see e.g. [152,138,139, 63,64,151,65,66,67,68,107,57,69,106,71,72,73,74].

1.3. Meta-theoretical frameworks for the scalability issue presentation

Scalability might be investigated following different meta-theoretical frameworks. Meta-theory is a 'theory about theory', the theory treated by the meta-theory being designated 'object-theory'. Following [134]:

> "A meta-theoretical perspective, . . .is) a critical framework for analysis, and create a structure that enables elements of different theories and concepts to be located relative to each other."[2]

Concerning the scalability, the purpose of a Meta-theoretical framework for scalability research and implementation is to provide a better understanding of scalability as well as to improve the capability for effective and efficient development, implementation and validation of scalability.

In the literature, no explicit reference can be found to any meta-theoretical framework, or taxonomy of problematics that refer to the issue of scalability investigation. Therefore, the meta-theoretical framework 'per se' that could be identified in the literature are only implicit and on an 'ad-hoc' basis.

Making this question explicit, as a first approach two criteria for structuring the scalability investigation meta-theoretical framework[3] are analyzed:

1. scalability functional and application domains;
2. scalability abstractions hierarchy.

1.3.1. Scalability functional and application domains framework

Manufacturing system (MS) scalability functional and application domains could be identified through analysis of MS models. One of the models, at a very high level of abstraction, that may however represent a global reference model for scalability investigation, could be illustrated as in Fig. 3. It is presented in IDEF0 graphical language depicting three main global processes of a manufacturing system and global "input", "output", "control" (i.e. control and/or management) and "mechanism" (i.e. instrument) entities. Each of these entities represents a possible functional area for scalability application. These are:

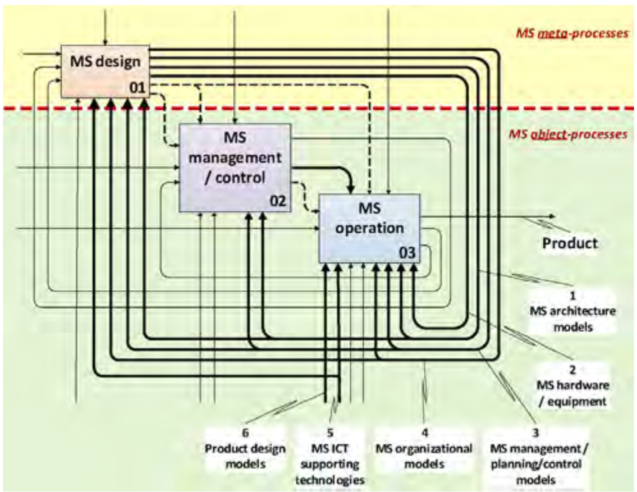


Fig. 3. Manufacturing System functional framework as a meta-theoretical framework for scalability investigation.

• Processes	01 MS design 02 MS management/control 03 MS operation
• Instruments	1. MS architecture models 2. MS hardware/equipment 3. MS management/planning/control models 4. MS organizational models 5. MS ICT supporting technologies 6. Product design models

"*Transitive*" *and* "*reflexive*" *ways of scalability applications*: The 'MS design' process could define that the 'MS management/control' process will be executed and managed as scalable, but the same 'MS design' process could also define that this very process will be executed and managed as scalable. This is valid also for the 'MS

[2] Minor adaptations of the original text were made by the authors of this paper.

[3] Other frameworks are possible too.

operation' sub-processes. In other words, it is to say that for all 'processes' in the above process taxonomy, scalability could be applied/implemented, in a transitive or reflexive way, i.e. *referencing* (to the object system), and/or *self-referencing* (to itself). This is presented in Fig. 3 where for example the scalability solutions produced by the 'MS design' process are used as the instruments by the 'MS management/control' and 'MS operation' processes and their sub-processes, as well as the scalability solutions produced by the 'MS design' process are used by the 'MS design' process itself.

1.3.2. Scalability abstraction hierarchy framework

The abstraction levels hierarchy meta-theoretical framework, inspired by [134], presents a taxonomy of abstractions and their hierarchical ordering with the intention to 'externalize many of the hidden dependencies between' underlying concepts, elements and constructs of a theory, in our case of scalability. Considering concepts, elements and constructs of a theory on one abstraction level means that the concepts, elements and constructs of the theory are considered independently of, i.e. abstracted from, their 'domain-based meanings associated with' other abstraction levels. It means that although each "higher" level includes the "lower" levels' objects and constructs, these (the "lower" levels' objects and constructs) are abstracted within (making them decoupled from) the consideration on the "higher" level. However, it is not always fully possible to do that, due to possible interpretations, e.g. some objects and constructs might be considered as belonging to two, or even more, levels (this case is referred in the first paragraph of Section 4).

In this paper, the scalability abstractions will be formulated on 5 hierarchical levels:

- **Description**: scalability definitions, terminology, elements and objects (referring to application areas).
- **Models and behavior**: models and functions, performance measures.
- **Mechanisms of choice**: scalability management.
- **Methods and tools**: scalability implementation instruments (hardware, equipment, architectures, strategies for implementation, design for scalability).
- **Epistemology**: how the knowledge on scalability is acquired and used, validity and coherence of knowledge on scalability in social context, scalability phenomenology, critique (e.g. limits and sense), human and social dimension (e.g. value), and other epistemological issues.

1.3.3. Selection of the meta-theoretical framework for the scalability issue presentation

The selection of the meta-theoretical framework for the scalability issue presentation might be important for some specific objectives of the presentations, otherwise it is an arbitrary choice. For this paper the scalability abstraction hierarchy based meta-theoretical framework is selected.

> Limitations I:
> In this paper the 'product' scalability *will be not* presented due to the limited space, although it might be considered as an issue of manufacturing systems in general and is presented as an entity of the functional model in Fig. 3.

2. Description

2.1. Definitions and terminology

2.1.1. 'Scalability' general meaning

The term 'scalability' (noun) is derived from 'scalable' (adjective) which is derived from 'scale' (noun or verb). Etymologically 'scale', as a verb, means "to climb," late 14c., from Latin *scala*, from *scandere* "to climb" (see **scan** (v.)). Modern use of the terms 'scalability', 'scalable', 'scale' provided other meanings, through the language change.

For our purpose more relevant meanings of 'scale', when verb, are "*tr* to make or draw (a model, plan, etc.) according to a particular ratio of proportionate reduction", "*tr*; usually followed by up or down to increase or reduce proportionately in size, etc." [38]. Relevant meanings of the adjective 'scalable' are "(*computing*) (of a network) able to be expanded to cope with increased use" [38], "capable of being easily expanded or upgraded on demand <a scalable computer network>" [144] "a business or system that is scalable can successfully grow larger using the same methods", "used to describe a system that can be made larger, for example by adding extra hardware, or deal with extra work without affecting its performance", "used to describe computer graphics (= pictures) that can be increased or reduced in size" [31], and similar.

2.1.2. Two principles of scalability implementation in manufacturing systems

Concerning manufacturing systems, as well as Computer Science, new or derived meanings are created in order to accommodate the inherent needs. There are two relevant meanings/principles when referring to "scalability in manufacturing systems", as well as "scalability" in general, followed by scalability implementation principles in manufacturing systems, see Fig. 4a and b, respectively [82]:

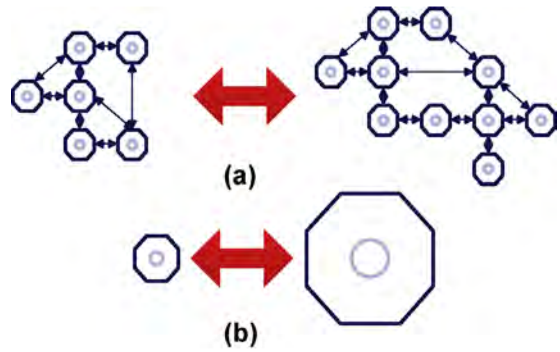


Fig. 4. (a and b) Two principles of scalability implementation relevant for Manufacturing Systems. Adapted from [82].

First principle:

"Several identical elements of the architecture may be linked together to provide scaled performance or functionality".

Second principle:

"A single element of the architecture may be scaled by up/downsizing its characteristic parameters".

In the context of the 2nd principle, the characteristic parameters could be the 'size' or 'structural' parameters on various magnitudes of scale, from macro (large and very large) to micro and nano magnitudes of scale.

The theoretical foundations for analysis and implementations of the scalability for the two principles are rather different in nature (the theoretical foundations for scalability by the 2nd principle are based on the theories of *dimensional analysis, scale analysis* and *similarity theory*).

Similarly, both principles could be combined in an implementation, presented as in Fig. 5, in the context of CompSci using the terms 'replication' and 'upgrade' for the 1st and 2nd principles, respectively.

Following the first principle, the systems, in our case manufacturing systems, need to have "the necessary capability for an unrestricted increase or decrease of total unit population within the system." [82].

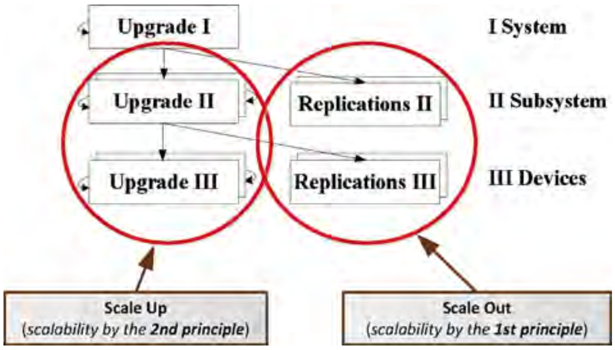


Fig. 5. Upgrade tree of scaling options. Adapted from [27].

Interpreting it in terms of manufacturing systems community, scalability (following the 1st principle) might be defined as:

> Scalability is the capacity for adding or removing the resources in a cost-effective manner, in order to "adjust the production capacity on a system in steps or stages". [119].

Limitations II:

In this paper scalability by the 2nd principle *will be not* presented due to the limited space, although scalability applications by the 2nd principle cover a very large and well established domain in both theory and practice, i.e. industrial applications, and could represent a particular theme.

2.1.3. Terminology and definitions

Beside the above definition there are a number of other formulations. These definitions come from a great number of solutions presented in the literature and "touted" as "scalable". However, it could be observed that not all definitions are consistent in relation to each other. That is, "Such claims to scalability are hard to refute (or prove) because scalability has no commonly accepted precise definition. There is, however, some consensus that as the size of a scalable machine is increased, a corresponding increase in performance is obtained." [154]. On the other hand, it is also observed that "the increase in performance is related to communication patterns in applications programs and the communication infrastructure provided by the machine" [154].

In what follows, a (not exhaustive) list of definitions and terminology is presented, Box 2.1, demonstrating the richness of terminology, use and interpretations in different contexts.

Box 2.1. Scalability selected definitions and terminology

Scalability – ''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.'' [177].
Scalability – ''System scalability is defined as the design of a manufacturing system and its machines with **adjustable structure** that enable system adjustment in response to market demand changes. Structure may be adjusted at the system level (e.g., adding machines) and at the machine level (changing machine hardware and control software).'' [116].
Scalability – ''The notion of scalability implies that where the problem size increases, the algorithm continues to apply and, by increasing the number of computational engines proportionately, the performance of the algorithm will continue to increase.'' [85].
Scalability – the ability to grow the power or capacity of a system by adding components [50].
Scalability – is a capacity of ''realizing evolutionary implementations that achieve minimum total-installed cost (TIC) per function deployed, and the minimum total-operating-cost (TOC) over the system's life cycle.'' [20].
Scalability – ''of a given architecture'' is defined ''to be the fraction of the parallelism inherent in a given algorithm that can be exploited by any machine of that architecture as a function of problem size. For a given algorithm and problem size, we derive the inherent parallelism as the ratio of the serial execution time and the runtime on an ideal realization of a parallel random access machine (PRAM). For the same algorithm and problem size, we then derive the maximum speedup attainable by a machine of any size with the architecture of interest.'' [154].
Scalability – ''the ability to access services across the shop floor or around the world using the same'' [90].
Scalability – an architecture is scalable with respect to an IT profile and a range of desired capacities if it has a viable set of instantiations over that range [27].
Scalability – in terms of user load, the application needs to be able to scale to a large number of users, potentially in the millions.
– in terms of data load, the application must be able to scale to a large amount of data, potentially in petabytes, either produced by a few or produced as the aggregate of many users [168].
''*Scalability* is the ability to change the level of a parameter.'' [166].
Scalability – means that ''applicability is independent of product, process, customers and supplier relationship complexity'' [202,60].
Algorithms scalability – ''The algorithm is scalable in the sense that problems of equal size have the same speedup when the number of processors increase because the communication is reduced from global to local and, thus, the solution depends on direct neighboring processors.'' [16].
Computational scalability – operations on the data should be able to scale for both an increasing number of users and increasing data sizes [168].
Downward scalability – deals with parts of the NVE being connected to systems with large computational power, necessary for example to support the rapid transmission of massive data sets required by tele-immersive applications [17].
Economic scalability – measuring system efficiency and capacity as a function of required resources. Efficiency represents the amount of resources needed to deliver a unit of service [96].
Elastic scalability – ''implying that the resources are put to use according to actual current requirements observing overarching requirement definitions – including both up- and downward scalability'' [170].
Geographic scalability – the ability to maintain performance, usefulness, or usability regardless of expansion from concentration in a local area to a more distributed geographic pattern [158].
Horizontal scalability – the ability for a system to easily expand its resource pool to accommodate heavier load [158].
Horizontal scalability – ''refers to the amount of instances to satisfy e.g. changing amount of requests'' or, ''instance replication'' [170].
Ideal system scalability – constant efficiency and a linear rate of change in capacity [96].
Qualitative scalability – ''depends, on the other hand, on scaling the complexity of social relationships from simple interactions to creating organizations or even further to forming artificial societies with increasing agent complexity, i.e. improving the abilities of agents to deal with complex situations, as well as increasing problem complexity, i.e. the complexity of the overall objective the MAS was designed for.'' [78].
Quantitative scalability – ''depends on quantitative changes in parameters like resources and number of agents'' [78].
Sideways scalability – enables the dynamic grouping of these participants into crowds or smaller awareness or interaction groups [17].
Upward scalability – refers to the number of objects and users that the system can support [17].
Vertical scalability – ''refers to the size of the instances themselves and thus implicit to the amount of resources required to

maintain the size'' or, ''changes in the resource structure'' [170].
Scale agility – in order to scale to increasing or decreasing application load, the architecture and operational environment should provide the ability to add or remove resources quickly, without application changes or impact on the availability of the application [168].
Scale Up – expanding a system by incrementally adding more devices to an existing node, typically by adding cpus, disks, and NICs to a node [50].
Scale Out – expanding a system by adding more nodes, complete with processors, storage, and bandwidth [50].

2.2. Scalability in the context of adaptability, flexibility, reconfigurability, changeability and robustness

One pertinent question relates to the scalability relationship with adaptability, flexibility, reconfigurability, changeability and robustness. In other words, considering that the literature, at least for the issue of flexibility, is vast, the question could be formulated as if, e.g., flexibility subsumes scalability.

In this respect there are important works that provide a deeper view on the issue of scalability relationship to adaptability, flexibility, reconfigurability, changeability and robustness, e.g. [202,58,166,82]. By [82] "Scalability ... is a key to flexibility, agility, and adaptability". However, further inquiry of the issue is required.

Similar to many concepts (as for scalability, see above), there are different definitions of adaptability, flexibility, reconfigurability, changeability and robustness, which imply that scalability should be contextualized considering them. In what follows, three contexts will be presented (the number of contexts is virtually phenomenologically and practically unlimited).

1st context

Within this context there is a clear difference in definitions of *flexibility* and *reconfigurability*. For example

> "Traditionally flexibility is interpreted as the ability of a system to change its behaviour without changing its configuration. Conversely reconfigurability is interpreted as the ability to change the behaviour of a system by changing its configuration." (T. Tolio in [202]).

Considering further the reconfigurability, changing behavior is possible without scalability. As scalability implies changing configuration by adding (or removing) the configuration elements, it is clear that scalability is a subset of reconfigurability, i.e. a subset with specific properties, and distinct from flexibility, Fig. 6.

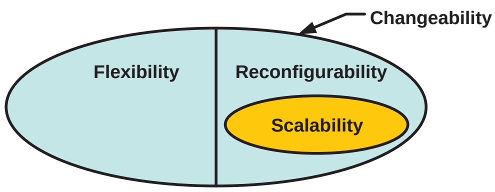


Fig. 6. Scalability as a subset of reconfigurability and distinct form flexibility.

2nd context

Within the 2nd context, the definition of flexibility is a very wide, implying any kind of changes, including reconfigurability. In [202] refers to 'conversion flexibility':

> "Conversion flexibility is very much like reconfigurability. Here, complete workstations are exchanged and replaced, e.g. from automatic stations to manuals stations."

By this view, scalability is clearly a subset of both, flexibility and reconfigurability, Fig. 7, being all part of *Changeable Manufacturing*.

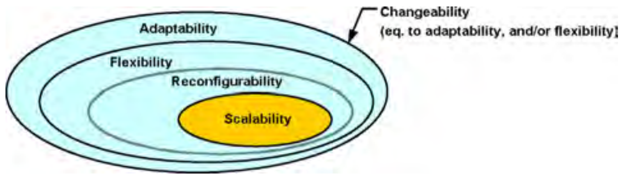


Fig. 7. Scalability as a subset of both flexibility and reconfigurability.

In this context, scalability is one of the principle enablers of Changeable Manufacturing [202].

It is possible to claim that scalability is one specific form of flexibility and reconfigurability, or changeability. Additionally, it should satisfy a specific requirement of linearity (or almost linearity) of the effect as a function of the scalability of resources. Actually, this property of the scalability is virtually the most important one.

An analysis of the literature on flexibility (in the first place) and changeability would show that virtually all other aspects of flexibility and changeability are much more investigated than its form of scalability, making scalability a major the topic of investigation by seeing it as a still unexplored potential.

3rd context

Scalability may be analyzed in the context of changeability together with *robustness* and *modifiability*.

> "The changeability of a system can be classified into three categories of effects: robustness, scalability, and modifiability, ... A system can be described in terms of sets of parameters, which capture physical, functional, and other performance aspects.
>
> Robustness is the ability to remain "constant" in parameters in spite of system internal and external changes. Scalability is the ability to change the level of a parameter. Modifiability is the ability to change the membership of the parameter set." Fig. 8 [166].

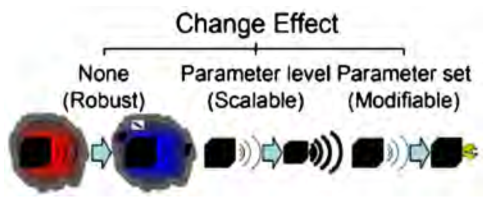


Fig. 8. Change effect for distinguishing between robustness, scalability, and modifiability [166].

Considering that a "constant", fixed, unchanged, system is not an ultimate goal for a user, or society at the end, but rather to remain 'robust' in capacity of delivering 'value' (see [190] too), changeability is seen as an instrument to achieve this goal, and, consequently, scalability is a specific instrument.

This provides us the perception of scalability as an active "mean" in providing the capacity of value creation. In this context, scalability could be also considered as a mean to use in co-creative systems for value creation.

2.3. Elements and objects/aplication areas

The number of scalability application areas is apparently under steady growth, as can be evaluated from the statistics of number of relevant papers published per year, see Figs. 1 and 2. In the following, some applications are listed, primarily for the global area of manufacturing systems, and then for CompSci of importance for manufacturing systems. The listed applications

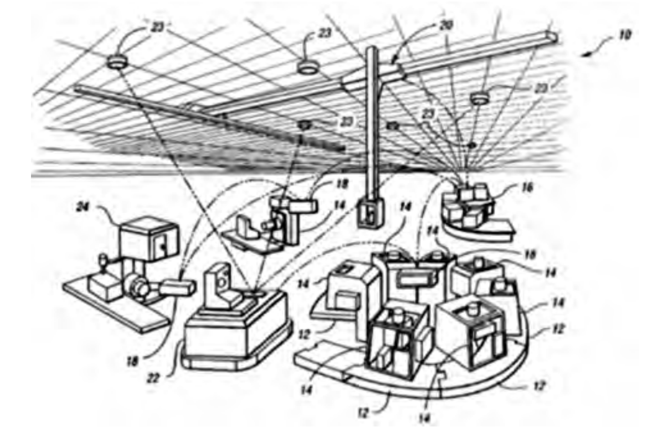


Fig. 9. Reconfigurable manufacturing system – the illustration from the patent US 6,349,237 B1 [118].

do not represent an exhaustive list but rather exemplify the concepts.

2.3.1. Manufacturing systems

Scalability is one of the key characteristics of reconfigurable manufacturing systems (RMS), figuratively presented in Fig. 9 [118].

Scalability was introduced in a CIRP keynote paper as a core requirement of RMS. It was noted there that capacity scalability should be obtained by building the RMS with an adjustable structure [112].

A discussion on paradigmatic aspects of flexible manufacturing systems and RMS, including a discussion on scalability, is presented in [58]. An overview of RMS is presented in e.g. [23] and [137].

In [119] the impact of different manufacturing systems configurations on capacity scalability and its cost is evaluated.

Ref. [175] explores scalability in the context of line balancing for RMS.

Ref. [176] reports the scalable reconfigurable equipment design principles.

A rigorous mathematical design method for RMS with examples of scalability are presented in [115].

Ref. [15] refers to scalability as one of the issues related to concepts, research, and applications of RMS.

Scalability, as one of the conditions for guarantying the deadlock-free operation within flexible manufacturing systems (FMS) operation, is investigated in [124].

Within the Holonic Manufacturing Control, by [29], scalability is one of the implications when developing "highly flexible manufacturing operations".

Ref. [44] reports a model related to capacity scalability policies in RMS. The same authors in [45] address the capacity scalability delay, as one of the sources of the operational complexity of dynamic capacity in multi-stage production. Furthermore, the optimal capacity scalability scheduling, in a cost effective manner, in a RMS is investigated in [46].

Ref. [202] refers to Changeable Manufacturing, and, more specifically to Production Planning and Control (PPC).

In [155] scalability is one of the parameters within a "method for evaluating the actual as well as the target transformability of a factory".

Scalability is also referred to as one of the requirements for Additive Manufacturing whether directly referred, e.g. [24] or by development of the equipment that could be instruments of (system, organizational, or business) scalability.

Scalability is also inherent in flexible, modular and reconfigurable Assembly Systems (AS), e.g. [12,11,76,212,22]. Although sometimes not referred explicitly as scalable, scalability is implicit as e.g. modularity of AS are in fact one of the scalability instruments and could be used for scaling up and down the AS, Fig. 10 [97].

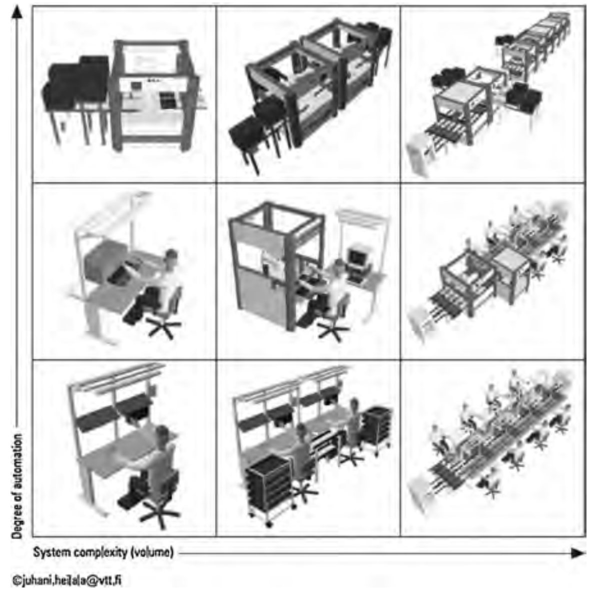


Fig. 10. Modular assembly system matrix [97].

2.3.2. ICT in manufacturing

Scalability in the area of ICT in manufacturing is a wide area that follows achievements in Computer Science. The scalability of the ICT in support of manufacturing is often implemented implicitly without explicit reference to the requirements and solutions for scalability.

Further, some examples of scalable ICT applications, which are explicitly referenced, are presented. The areas of Multi-agent System (MAS), e.g. [185], sensor networks, e.g. [186], and cyber-physical systems are selected as sub-areas where the scalability is investigated more systematically, or has a wider impact for the areas as a wholes.

Multi-agent System (MAS)

The scalability in MAS refers primarily to the issues of (1) Number of Agents in the System/Host, (2) Resource Consumption of Agents and (3) Number of Messages [49,28]. Also, by [203], "the scalability of a network of agents is in fact a simple property of telecommunication networks". By [129] "the scalability of a multi-agent system depends on whether the worst-case performance of the system (i.e. its overall algorithmic complexity) is bounded by a polynomial function of the load". Ref. [189] identifies that the "MASs should be *self-building* (able to determine the most appropriate organizational structure for the system by themselves at run time) and *adaptive*" and presents too an overview of the scalability research themes.

Sensor networks

Sensor networks is another growing area in which the scalability is one of the central issues. This is because the sensor networks nowadays imply the large-scale networks with "thousands of readers distributed across and within organizations that generate large volumes of data automatically and rapidly" [207] with data volumes that reach multiple tera-bytes of data generated every day [207]. That is, the scalability issues for the sensor networks are data volumes, integration, traceability, real-time data management, protocols, and others, see e.g. [42,53,132,146,188]. The sensor networks' importance is related to different MS models of which the collaborative manufacturing alliances [102], Internet of Things [133], and Real-Time Management, see e.g. [103,172], are highlighted.

Cyber-physical systems

Although 'cyber-' and 'physical' are connected from the beginning of the 'cyber-', in the last years the *cyber-physical* paradigm is emerging as a new dimension of the engineering, and consequently, manufacturing systems, due to employment of new

CompSci technologies and new forms of work implying large groups of participants as well as "large number of devices and the huge amount of content shared and generated by users (and their devices)" [40], for which designing scalable solutions is critical.

Other topics related to ICT in manufacturing areas in which the scalability is addressed explicitly are e.g. open controller architecture [161], multi-robot team formation control [169], scalable data structures for real-time estimation of resource availability [149], remote monitoring and maintenance system [148].

Industrial video supervision [55], augmented reality applications [153], open scalable manufacturing execution systems (OpenMES) [99], machinery control system using mobile agents [196], multi-agent framework for decentralized grid workflow management in collaborative design [209], service publication, discovery and reuse in distributed collaborative manufacturing, in [210], deadlock-free operation for real-time resource allocation for flexible manufacturing systems (FMS) [124], holonic manufacturing control [29], etc.

2.3.3. Design

The scalability for the "design" area is primarily the issue of design environments and organization, i.e. of the design teams and their management. The question is how scalability of the design environments and/or design teams affect the design process and how it is addressed by the design process, e.g. [167].

In [128] a "self-configurable large-scale virtual manufacturing environment for collaborative designers" is proposed. It "shares the characteristics of large-scale virtual environment (LSVE) and virtual manufacturing environment (VME)." Scalability is one of the characteristics of LSVE and one of the eight characteristics of the proposed architecture.

It is important to notice that the 'dynamic reconfiguration' characteristic could be considered in direct relation to scalability. This would be relevant for any type of design team and its dynamic reconfiguration, as virtually for the case of "mass collaborative product realization" [75].

An analysis of scalability types appropriate for the collaborative design in Networked Virtual Environments (NVE) is presented in [17], Fig. 11. "Tools supporting collaborative design review must be able to support social interaction and the visualization of complex models. Software and hardware scalability are essential, as diversity of interfaces and systems may increase with multiple involved organizations" [17].

	Type	Value
Scalability	Upwards	Small
	Sideways	No
	Downwards	Yes
	Hardware	Yes
	Software	Yes

Fig. 11. Scalability types required for a collaborative design review environment [17].

One of the requirements of modern design environments is the visualization of complex objects, including tele-immersive applications, implying "enormous amounts of memory and processing power ... Therefore, complex virtual CAD systems must be downwardly scalable" [17].

2.3.4. Computer Science

Scalability issue in CompSci started already "several" decades ago when computers began to connect and when the "first high-performance architectures were emerging" [160]. It could be said that from that time scalability has become "a central design issue" in the "mainstream computer science" [49].

Scalability was investigated with the objective to "proportionally" increase the system's performance "with increasing system resources" [105]. Scalability is achieved by "the number of processors used, the memory capacity enlarged, the access latency tolerated, the I/O bandwidth, ... etc." [105]. Although scalability is achieved for both sequential and parallel architectures, the latter demonstrated a higher potential for scalability [105]. The scalability is a function of architecture-algorithm combinations, i.e. "both hardware and software issues" are studied in building scalable systems [105].

Due to the success in building scalable computer systems these "eliminated and replaced the previously established, more slowly evolving classes of the first period" [21].

"Scalable, multiple computers can be networked into arbitrarily large computers to form clusters that replace custom ECL and CMOS vector supercomputers beginning in the mid-1990s simply because arbitrarily large computers can be created. Clusters of multiprocessors were called constellations; clusters using low latency and proprietary networks are MPPs (massively parallel processors) ... Thus scalability allows every computer structure from a few thousand dollars to several hundred million dollars to be arranged into clusters built from the same components." [21]. Fig. 12 shows the IBM's Blue Gene/P massively parallel supercomputer [13] (see also "Blue Gene" on Wikipedia, http://en.wikipedia.org/wiki/Blue_Gene) (although newer architectures exist today, the example of Bleu Gene/P photo is visually very illustrative).

Fig. 12. IBM's Blue Gene/P massively parallel supercomputer from year 2007 [13].

Concerning software, "scalable architectures are especially important for large distributed applications such as social networking sites, e-commerce Web sites and services, and point-of-sale/branch infrastructures for more traditional stores and enterprises where the scalability of the application is directly tied to the scalability and success of the business ...

These applications have several scalability requirements: scalability in terms of user load, scalability in terms of data load, computational scalability, scale agility" [168].

The software applications "that stop scaling with Moore's Law, either because they lack sufficient parallelism or because their developers no longer rewrite them, will be evolutionary dead ends." [122].

In other words, scalability is the issue in virtually any of many application areas of CompSci, ranging e.g. from programming techniques and languages, software engineering, to information systems, distributed systems, social and behavioral sciences, web applications, cyber-physical systems, and others, including computer-aided engineering, in exploration and "harnessing the power of emerging technologies (such as petascale computing, exabyte data stores, and terabit networks)" [130].

Additionally, scalability becomes a central issue for emerging concepts related to collaborative and co-creative systems and any kind of group work (well present in manufacturing systems too). That is, "scalability becomes an issue, on top of all other challenges encountered in a simpler two-device setting. It turns out that only a few techniques workable in a two-device case are applicable to the group setting." [40].

Furthermore, just one application on scalable working environments is presented – "the Scalable Adaptive Graphics Environment, software ... serves as a cyber-mashup, enabling collaborators to simultaneously run applications on local or remote clusters. ... remote colleagues access and view multiple ultra-high-resolution visualizations, participate in high-definition videoconferencing calls, browse the Web, or show ... presentations ... (supporting) continuous interaction, ... and encourage mobility among team members and information", using "ultra-high-resolution 2D and autostereoscopic 3D display technologies, table displays, high-definition teleconferencing systems, laptops, and ubiquitous handheld devices" [130]. Fig. 13 illustrates such an environment.

Fig. 13. Future cyber-commons environment [130].

3. Models and behavior

3.1. Theoretical foundations

The 1st principle of scalability deals with parallelism of resources, by adding or removing resources in parallel, as required. The requirements for parallelism, i.e. for scalability, could be formulated in different ways, such as [95]:

1. solve given problem in less time,
2. solve larger problem in same time,
3. obtain sufficient memory to solve given (or larger) problem,
4. solve ever larger problems regardless of execution time.

The question is on metrics of how much is the gain by employing parallel processors, what are the measures and what are their factors. Which are the properties of a parallel system, or of the process of parallelizing, that make one system as scalable, etc. The literature on these questions and on formalization of the models to define scalability is vast, especially in the Computer Science literature (including a number of textbooks), e.g. [105,88,154,98,135,156].

The investigation of a parallel system properties starts from defining the speedup of the system by adding resources, or processors. If *time*(*n*, *x*) is denotes the time required by an *n* resources, or processors, system to execute a program of size *x*, then "the *speedup* on a problem of size *x* with *n* processors is the execution time on one processor divided by the time on n processors, or" [98]:

$$speedup(n,x) = \frac{time\,(1,x)}{time\,(n,x)}$$

speedup divided by the number of processors defines the *efficiency*, or:

$$efficiency\,(n,x) = \frac{speedup\,(n,x)}{n} = \frac{time\,(1,x)/n}{time\,(n,x)}$$

Following, "the best possible efficiency is one, implying the best speedup is linear, *speedup*(*n*, *x*) = *n*. ... Therefore, a restrictive definition of scalability is" (ibid.):

> A system is scalable if efficiency (*n*, *x*) = 1 for all algorithms, number of processors n and problem sizes *x*.

Or, in other words [182]:

> Scalability is a property that exhibits performance linearly proportional to the number of processors employed.

One important measure for scalability is "*isoefficiency*", defined by [88]. The isoefficiency function "characterizes the increase in raw workload which a system requires to maintain constant efficiency as more resources are added to it. ... One system is more scalable than another if it has a slower-growing isoefficiency function." [96].

However, the above represents the case of ideal parallelism, called "linear scalability". In reality, as observed by G. Amdahl [9], "ideal parallelism cannot be achieved in general because there are certain portions of the workload that can only be executed sequentially (gray). The aggregate portion of the total execution time is called the serial fraction" [91], Fig. 14.

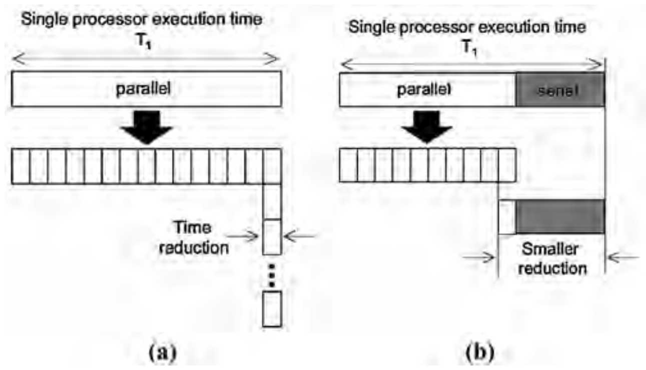


Fig. 14. (a) In ideal parallelism the uniprocessor execution time T_1 is reduced to T_1/p by equipartitioning the workload across *p* physical processors. (b) Certain portions of the workload can only be executed sequentially [91].

By Amdahl's Law the speedup is defined as

$$speedup = \frac{1}{r_s + (r_p/n)}$$

where $r_s + r_p = 1$, and r_s represents the ratio of the sequential portion in one program [9].

By Amdahl's Law the efficiency is non-linear and diminishing with number of processor growing, see Fig. 15, approaching asymptotically to an upper bound.

However, the Amdahl's Law has defined the scalability law for specific conditions. Under different conditions scalability may be better than that obtained by Amhdahl's Law. One such case is defined by the well-known Gustafons's Law [94].

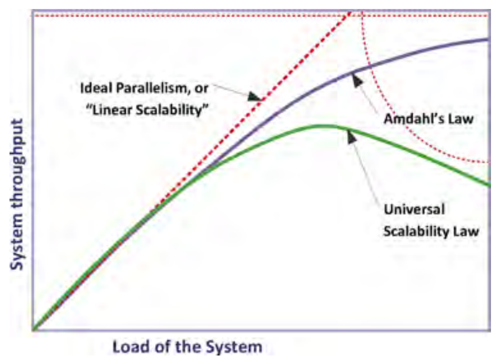


Fig. 15. Linear scalability, and scalability by Amdahl's Law and by USL [93].

A further development is the formulation of the Universal Scalability Law (USL) [91,92]. The USL model is a rational function:

$$C(n) = \frac{n}{1 + \alpha(n+1) + \beta n(n-1)}$$

The three terms in the denominator are [92,93]:

1. Ideal concurrency associated with linear scalability (α; $\beta = 0$) – metaphorically "Equal bang for the buck".
2. Contention-limited scalability due to serialization or queuing ($\alpha > 0$; $\beta = 0$) – this term represents cost of sharing resources and diminishing returns at higher loads.
3. Coherency-limited scalability due to inconsistent copies of data (α; $\beta > 0$) – negative return on investment (Fig. 16).

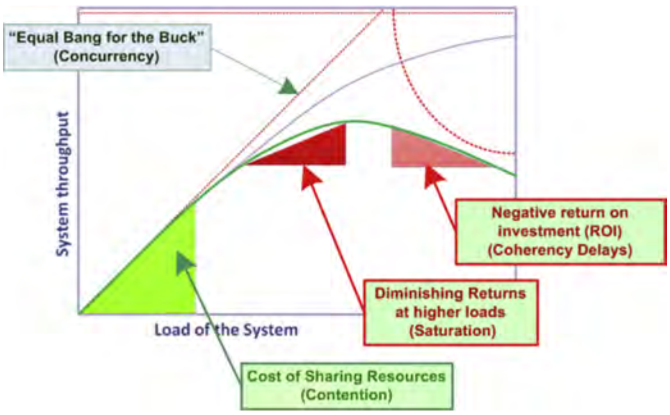


Fig. 16. Scalability regions [93].

"The USL model corresponds to the synchronous throughput bound of a load-dependent machine repairman." [92].

Fig. 16 presents the form of the scalability function by the USL, with the "regions" corresponding to the three terms referenced above. It implies that in reality there is no absolute scalability, that the point of "maximum" exists and that after that point there would be even a negative return.

Therefore, the analysis of the scalability functions for the particular cases in manufacturing systems is critical, as well as for orienting the further development of instruments for improving scalability of the systems under consideration.

On the analytical level the scalability analysis in the first place analyzes the scalability function, characterized by "shape, domain and increment size". The shape indicates whether the system is in the domain of linear scalability or in the domain of "economy or diseconomy of scale", while the domain and the increment size defines the system boundaries and the "range of values which the size variables can take in practice" [27].

An example of analysis is related to the concept of "economic" scalability, Fig. 17 [96]. Economic scalability is described in terms of system efficiency and capacity as a function of required resources. Efficiency represents the amount of resources needed to deliver a unit of service while capacity represents the maximum rate of service that a system can handle. "One architecture has better economic scalability than another if its efficiency and capacity functions grow faster." [96]. However, the isoefficiency function, by its very name, "suggests that ideal scalability keeps efficiency constant, which makes economic scalability impossible." [96].

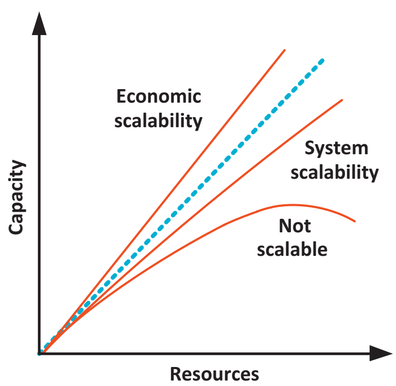


Fig. 17. Economic scalability must improve the performance-price ratio superlinearly [96].

The analysis should also consider a number of factors such as e.g. congestion effects – as a result of competition for resources, software effects and platform effects related to the set of subsystems or devices, which supports the processes at a particular level [96]. Fig. 18 presents some scalability parameters, or "metrics" [105].

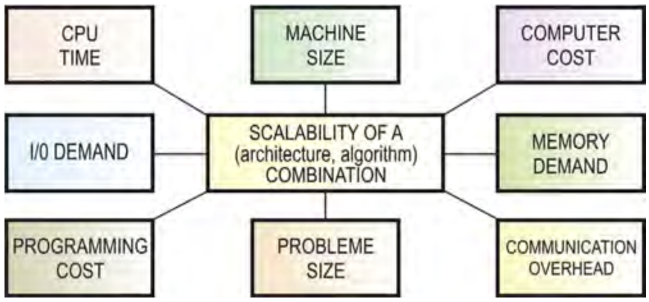


Fig. 18. Scalability parameters, or "metrics" [105].

3.2. Scalability models in manufacturing systems

Scalability models for manufacturing systems (MS) in analytical form are primarily developed in the area of RMS. Although the terminology is different than the one used in the previous section the nature of the scalability phenomena is fully addressed referring to the same type of factors and effects.

In [117] a simple definition of scalability is presented which could be considered as a definition of "ideal" scalability for MS as it neglects factors such as queuing, latency, and others. Scalability is defined as

$$\textit{System scalability} = 100 - \textit{smallest incremental capacity}\ [\text{in percentage}]$$

By the model defined, e.g. for configuration (a) in Fig. 19 *Scalability* = 0, as the smallest increment of adding new production capacity is the whole line, i.e. 100% of the system, and for configuration (b) has the scalability of 50%, etc.

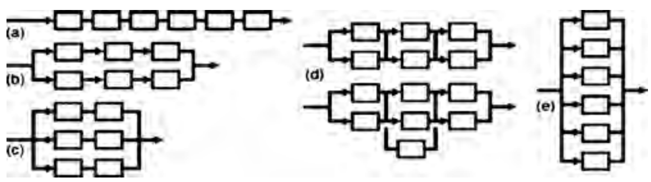


Fig. 19. Five configurations with different scalability [117].

The scalability model for designing a scalable machine tool is presented in [176]. The scalable machine tool is a kind of modular machine, where the equipment modules can be added to a base machine structure and later removed, rearranged or replaced as required, providing the machine scalability. Therefore, the number of sufficient module positions, in order to facilitate the necessary changes in capacity, is a distinguishing feature of the scalable machine tool. An example of a four-spindle Scalable multi-spindle CNC (SMS-CNC) is presented in Fig. 20.

The scalability model in this case is a more elaborated model whose objective is to define the maximum number of the machine

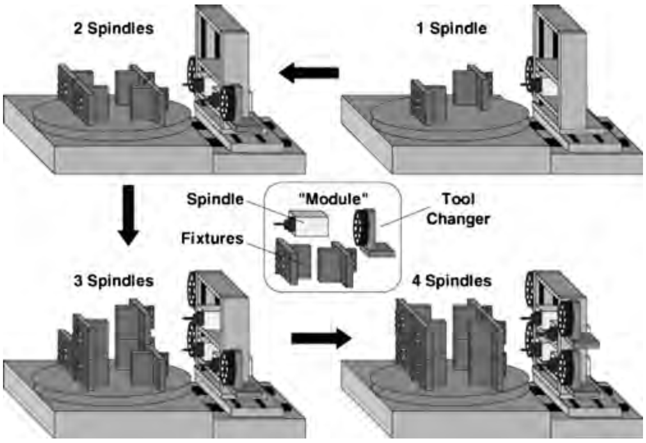


Fig. 20. Four-spindle SMS-CNC [176].

modules after which the number the additional modules will not increase the machine's production rate.

The model is defined in the following way.

If A_M is the probability a module's availability to run the maximum number of modules is obtained:

$$n_{\max} = \frac{-1}{\ln(A_M)}$$

However, the $n_{\max}$ above is not necessarily the cost-optimal number of module positions that should be available on a scalable machine. In fact, the cost-optimal number is smaller.

A model for manufacturing systems scalability is introduced in [198]. The model factors are configuration of the system, stage characteristics, manufacturing tasks, machine reliability information and demand. The decision variables are: (1) number of machine $M[i]$ being added to stage i, and (2) index of stage s, $T[i]$ = s, to which the task i is assigned. The objective of the scalability model is to minimize the number of machines needed to meet a new market demand, which is modeled as:

$$Minimize\left(\sum_{i=1}^{L}(N_l + M[i])\right)$$

where N_i represents the number of machines in each stage.

Another model for scalability of manufacturing systems, i.e. for RMS, is presented in [45]. The model is defined for a multistage production, as a stochastic dynamic model for the capacity problem.

It should be underlined that the use of system dynamic theory for the scalability modeling [45] represents an important contribution to the scalability theory, Fig. 21.

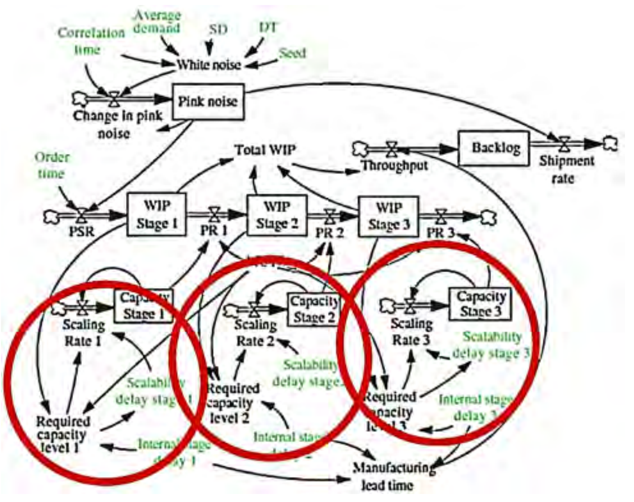


Fig. 21. Dynamic capacity model of the three-stage serial production system with depicted scalability related terms [45].

The scaling rate SR_i at each stage is determined by the required capacity together with the scalability delay time SDT:

$$SR_i(t) = \frac{C_i(t) - RC_i(t)}{SDT_i}$$

where $C_i(t)$ represents capacity level at time t at stage i, and $RC_i(t)$ represents required capacity at time t at stage i.

The required capacity RC_i is calculated based on the work in progress (WIP) level since the system is modeled as a work in WIP-based controlled system.

A similar model is developed in [48]. A model for a "new hybrid scaling policy" is proposed. The hybrid policy is defined as a capacity policy that considers "the demand rate, the current system's WIP level and the system's backlog when deciding on the capacity scaling value". The contribution is represented by considering both external and internal uncertainties.

3.3. *Cost modeling for scalability*

A conceptual framework for the scalability cost modeling is presented in [166] as a part of a wider framework for the changeability modeling. Scalability could be evaluated in the context of cost functions in terms of cost to develop the scalability C, through the mapping f_C: $\{DV^N\} \rightarrow C$, described as:

$$\text{scalability } y_i^m : \sum_j [[F_{XM}(\{DV\}_j)]^m - [F_{XM}(\{DV\}_j)]^m \neq 0 \text{ for } T_{ijk} < \hat{C}], \ \forall j \in S, \ K \in R$$

The mapping is instantiated through the particular cost models. Fully enumerating all possible values for the set of design variables results in a space of designs, that forms the so-called "tradepace".

Considering the concrete scalability cost models structures, the scalability cost in general is a compound of the cost of scaling and the cost of the instruments that provide scalability, following the well-known pattern of Fig. 22 [82]. Further developments of the scalability cost models actually refer to specific models integrating the specific variables and criteria.

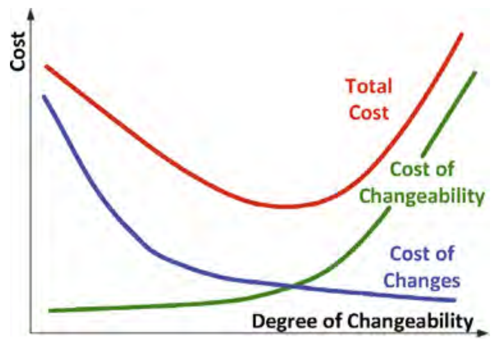


Fig. 22. Degree of changeability vs. sources of cost [82].

Cost modeling for manufacturing systems scalability is necessarily based on the scalability "behaviour" models formulated (see the previous section) and, in fact, represent their extensions by inclusion of different types of costs as variables.

In [176], for the case of scalable machine tools, the maximum, i.e. optimal, number of machine modules for the cost optimal solutions are modeled as follows.

If CB is the cost of the base machine, and CM is the cost of a module then the optimum number of modules n^* occurs when the production rate per unit of cost of a machine with n modules, G_n, is at the maximum, giving the value for n^*:

$$n^* = \left\lfloor \frac{-C_B \pm \sqrt{C_B^2 - 4C_M(C_B/\ln(A_M))}}{2C_M} \right\rfloor$$

An early analysis is presented in [119] in which three types of costs are considered, namely the machine cost, the cost of tooling per machine and the initial system cost.

A more detailed model, including more relevant variables is presented in [117].

In [43], the effects of reconfiguration costs on planning for capacity scalability in reconfigurable manufacturing systems is modeled and analyzed. The model incorporates both the physical capacity cost (C_t), based on capacity size, and costs associated with the reconfiguration process which referred to the scalability penalty cost (P_i) and scalability effort cost (SE_t):

$$C(v) = \sum_{t=1}^{T} C_t(v_t) + \sum_{i=1}^{n} P_i + \sum_{t=1}^{T} SE_t(v_t)$$

The model is used for the development of optimal capacity scalability plans. Fig. 23 shows different scalability schedules' costs as a function of different values of capacity planning time horizon (T).

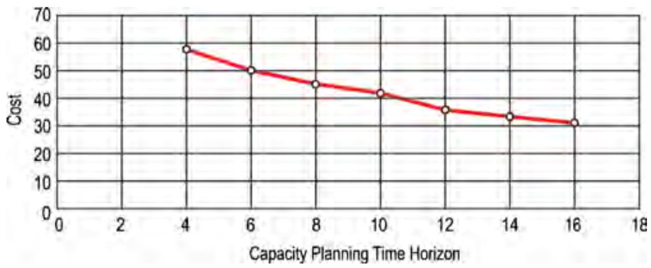


Fig. 23. The different scalability schedules' costs versus different values of capacity planning time horizon (T) [43].

In [175], for a form of RMS, called homogeneous paralleling flow line (HPFL), the system life cycle cost is modeled in the context of the system scalability. The system life cycle cost is also modeled for the uncertain demand. Fig. 23 shows the relation between the different scalability schedules' costs versus different values of capacity planning time horizon (T).

4. Mechanisms of choice: scalability management

Management is a very broad area that includes organizing, planning, controlling, directing, the organization, the system, or enterprise. It uses a number of tools, some of which (the tools) are the scalability models presented in Section 3. That is, phenomenologically the mechanisms of choice are practically based, if not equal to, the models presented in Section 3 and others, i.e. scalability models on capacities, throughput, cost, etc. One of the criteria for separation of the scalability related models groups could be that in the first group, presented in Section 3, there are the models that presents the scalability functions properties, oriented to different objects, and systems by different criteria (e.g. throughput, cost), while in the second group, to be presented in this section, there are the models that describe the forms and condition of scalability implementation management and use, which are the models on a higher abstraction level.

4.1. In manufacturing

In [46] the authors investigate optimal capacity scalability scheduling in a reconfigurable manufacturing system by comparing the three strategies for the capacity planning, of which the second and the third are in fact the case of system scalability, i.e. strategies of scaling employing the scaling operations management, in contrast with the first strategy. Furthermore, although the second and third strategies are scaling strategies they represent actually two different models of system scalability, considering different sets of conditions. Scalability management would imply a decision on whether to employ or not as well as, in the positive case, which model of scalability should be employed. This level of decision is obviously not supported by the particular scalability model addressing only its own properties. [44] presents a model for assessing different capacity scalability policies in RMS for different changing demand scenarios, which could be interpreted as a scalability management model.

In the case of lean cell design and management, in [48] the recommendations for the scalability implementations are formulated.

Similar decisions on the type of the scalability instrument to be employed as well as whether or not to employ scalability could be based on the analysis of alternative solutions, e.g. those presented in Table 1 [176].

Table 1
Machine scalability comparison [176].

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

In [30] a method for planning and developing flexible manufacturing systems is investigated. The decision to be made is on the selection of a control software development platform, that has the *major* implications in terms of cost, maintainability, and system scalability, where scalability is defined as the ability to add additional I/O points which may become critical as the system is modified over time. The authors proposed a general decision-making framework based on the weighted property index method. It may be seen that in the analyzed case, the importance weight of 10% is attributed to scalability.

In [155] a "method for evaluating the actual as well as the target transformability of a factory" is presented within which scalability is one of the parameters.

4.2. In Computer Science

Scalability management in CompSci is one of the regular issues.

For example, in [8] the authors proposed an innovative technique to support Risk Analysis associated with ERP projects. In this context, scalability (horizontal – number of factors, vertical – modeling details) is seen as one of the criteria "to judge the operation of a system or a technique" and as a component (among others) of the risk factor "Inadequate IT system issue".

Another risk modeling for scalability projects is proposed in [2]. Fig. 24 presents the risk composition "of an incident caused by the inability to scale (that) manifests itself as a threat to . . . quality of service or availability" [2].

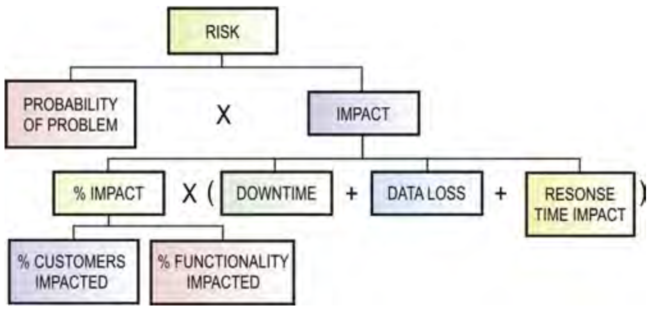


Fig. 24. Scalability and availability risk composition [2].

For scalability projects implementation management, the responsibility assignment in organization schemes is given in [1], Table 2. Different responsibilities are designated as 'Responsible' (R), 'Accountable' (A), 'Supportive' (S), 'Consulted' (C), and 'Informed' (I).

Table 2
RASCI matrix [1].

	CEO	Business Owner	CTO	CFO	Arch	Eng	Ops	Inf	QA	Board of Directors
Scalability Culture	R									A
Technical Scalability Vision	A	C	R	C	S	S	S	S	S	I
Product Scale Design		A			R					
Software Scale Implementation		A				R	S			
Hardware Scale Implementation		A					S	R		
Database Scale Implementation		A					S	R		
Scalability Implementation Validation		A							R	

In [27] a typical project management phases are recommended too for the scalability implementation project.

5. Methods and tools: scalability instruments

5.1. Designing for scalability – manufacturing systems

Ref. [47] presented a systematic design approach for RMS which subsumes the design of scalable manufacturing systems. The detailed framework is developed.

Similar frameworks are presented in other works related to RMS. For example, in [117] and [176] the design principles for reconfigurable machines (RM) are presented, which could be summarized as [117]:

1. The RM is designed with an adjustable structure that enables either machine scalability in response to market demands, or machine convertibility to adapt to new products.
2. The RM is designed around a part family with just the customized flexibility needed for producing all members of this part family.
3. The RM embeds a set of core characteristics in both its hardware and control structures.

The same design principles are also valid for the RMS level [117].

For the case of Real-Time Industrial Control [20] defines a design rule for implementing scalabiity successfully:

> "requirements for automation system scalability and adaptability" for Real-Time Industrial Control, satisfied by implementation a Distributed Programming model, "dictate adherence to a fundamental design rule: keep clear the separation between control policies and underlying implementation mechanisms, both within the system, and in its interactions with the plant processes under control."

Stage paralleling – is proposed against paralleling of the entire lines (a "traditional" approach) for the purpose of scalability in the context of line balancing for RMS [175].

Concerning flexible, modular and reconfigurable Assembly Systems (AS), modularity of AS is in fact one of the scalability instruments, as reported already in Section 2.3.1.

5.2. Designing for scalability – Computer Science

A great number of instruments are developed within the broad area of Computer Sciences, or ICT. They range from the hardware architectures to software architectures, services, software development and use management, and others. For example, see below.

Functional partitioning and/or *data partitioning* – represents the base for most of the "major architectural approaches that achieve high-level scalability", which implies "distribution of the work across many processing nodes" [168].

Service Broker(ing) – is referred in [168] as the instrument for providing "a communication fabric" that guarantees reliably delivering of messages to services. Additional services are still needed "for the developer to build massively scalable applications".

Open source – is the instrument used by "MYSQL" that allows customization permitting users to add their own requirements which adds to scalability [3].

Embedded applications – supported in large numbers by "MYSQL" adds to scalability too [3].

Reducing communication in parallel architectures – is the instrument "for achieving scalability of algorithms for resolution of very large problems" [16].

Increasing the ratio of computation/communication – i.e. increasing the size of the problem in each domain [16].

"*Scalability patterns*" – represent "architectural and design choices while designing a scalable system". The "Scalability Patterns Language Map" is presented in Fig. 25 [6].

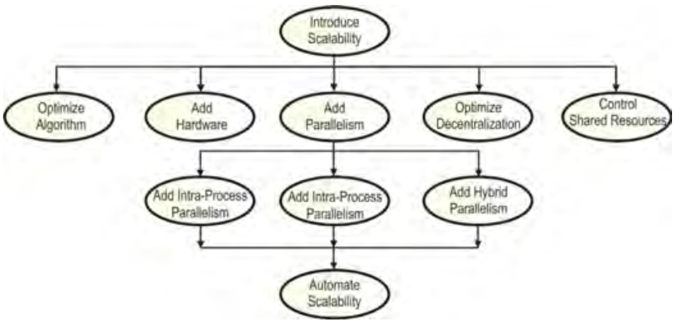


Fig. 25. Scalability Patterns Language Map [6].

Organizational aspects of design processes and teams scalability depend on "novel approaches that leverage automation, crowdsourcing, and user communities, as well as innovations that empower end users to create and modify their interfaces and to share these designs" [83] (also including already referenced "mass collaborative product realization"). This is because in "traditional" organizational approach scalability is virtually not feasible "because there are many individuals with unique abilities and needs" [83].

One of the instruments for enabling scalability is 'Automatic user interface generation', which "is a scalable approach and one that enables highly personalized and dynamic solutions" [83].

In [178] 10 rules are advised to customers for consideration "with an SO (Simple Operation) application and in examining non-GPTRS (general-purpose traditional row stores) systems". The rules are "a mix of DBMS (database management system) requirements and guidelines concerning good SO application design".

Rule 1	Look for shared-nothing scalability.
Rule 2	High-level languages are good and need not hurt performance.
Rule 3	Plan to carefully leverage main memory databases.
Rule 4	High availability and automatic recovery are essential for SO scalability.
Rule 5	Online everything.
Rule 6	Avoid multi-node operations.
Rule 7	Don't try to build ACID consistency yourself.
Rule 8	Look for administrative simplicity.

Rule 9	Pay attention to node performance.
Rule 10	Open source gives you more control over your future.

Abbott and Fisher [1] published a comprehensive guide to designing "*The Art of Scalability – Scalable Web Architecture, Processes, and Organizations for the Modern Enterprise*". The reference model for the application scaling, called "application scale cube", is given in Fig. 26.

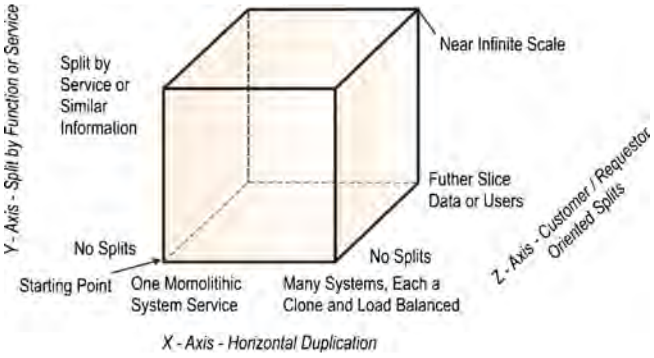


Fig. 26. AKF Application Scale Cube [1].

The same authors published another comprehensive text [2] in which they give in detail "50 Principles for Scaling Web Sites".

5.3. Other areas

Pilot plant – is an instrument representing "the intermediate facility ... for assuring effective scalability from R&D to full production" [87], particularly consider in pharmaceutical industry (manufacturing).

Regulations – is an instrument for enabling scalability from R&D to full production of particular interest in the pharmaceutical industry (manufacturing) as "any significant change in a process of making a pharmaceutical dosage form is a regulatory concern" [131].

5.4. Organizational slack – resources availability for scalability

Organizational slack is an interesting concept apparently not yet sufficiently investigated in the theory of manufacturing systems as it contradicts intuitively the "optimization", or (metaphorically) "lean" thinking. On contrary it is a known issue in organizational and related theories. The organizational slack is defined as [25]:

> "A cushion of actual or potential resources which allows an organization to adapt successfully to internal pressures for adjustment or to external pressures for change in policy, as well as to initiate changes in strategy with respect to the external environment."

For example, the slack resources might be in the form of redundant employees, unused capacity, unnecessary capital expenditures, etc. [193].

The organizational slack by its nature represents a cost within an organization. Despite that, from the organization theory point of view the organizational slack "has a positive impact on firm performance". On the contrary, from the agency theory point of view the slack "breeds inefficiency and inhibits performance" [183]. However, the empirical study (from an emerging economy) in [183] suggests "that organization theory is more strongly supported than is agency theory".

In the context of its positive impact, the slack could be seen as a specific resource when "organizational slack serves to reduce goal conflict, to reduce information processing needs, to promote political behavior, or to facilitate certain strategic behaviors" [25].

From the resource-based view of the firm (RBV) slack is also used to innovate and to employ novel services providing "a source of excess funds enabling search for innovations that would not be realized in times of shortness" [197]. In [193] the concept of overlapping knowledge across functions is considered as one type of slack, "that supports knowledge creation for innovation". Therefore, the slack, in the form of overlapping knowledge supports innovation.

In [84] the relationship between the slack and dismissal polices in companies and dismissal legislation is investigated. (Although the theme of dismissal policies virtually is not related to our interest it suggests the inverse theme on the relationship between slack and emergent manufacturing systems paradigms and employment, in the context of manufacturing systems (social) sustainability.)

The positive/negative impact of the slack depends on the strategy on the slack use and management as well as on the type of slack [36].

Now, the question is how the slack could be seen as an instrument of scalability in manufacturing systems?

Organizational slack is indirectly recognized as an important issue under the term of "redundancy" [204] – which might be interpreted as a form of slack, or, referred to implicitly in [198].

In [204] it is suggested that there should be an optimal balance of redundancies and efficiency at which the manufacturing system is most robust", which, further suggests that the slack serves as an instrument for robustness. (The nature of these results is in accordance with the nature of results in [183].)

While in [204] scalability is not referred, it might be interpreted that the introduction of redundant resources is a form of resources scaling out and that the capacity of introducing the redundancy is related to the level of scalability. Also, "the number of enough module positions" of a scalable machine tool, in [176] (see Section 3.2), which might not be used!, could be interpreted as a form of slack.

In [198] a form of slack, although the term slack was not used, is directly related to scalability. It is written: "From the cost-effective point of view, we suggest scalability planning be performed concurrently with the design of a new manufacturing system. This way, optimal locations where future machines should be installed can be identified in advance."

The term "location" implies physical space, and while waiting for the future machines to be installed, considering that that machines might not be installed at all, that physical space represents a slack. On the other hand, if no space is available no machines can be installed. Hence, it is concluded that:

> The organizational slack is an enabler, or an instrument, of scalability.

6. Emerging systems and architectures

In this section emerging manufacturing systems (MS), are presented, that are based on, or might be informed by, a certain number of CompSci technologies, systems and architectures that are relevant to scalability of MS.

6.1. Computer Science technologies, systems and architectures relevant to scalability of MS

These CompSci technologies, systems and architectures platforms are:

- *Grid Computing* (GC) (see e.g. [77,79]);
- *Ubiquitous Computing* (UC) (see e.g. [199,200]);
- *Internet of Things* (IoT) (see e.g. [145,18]);
- *Cloud Computing* (CC) (see e.g. [170,141]);
- *Web 2.0, 3.0, 4.0 (...)* (see e.g. [14,123]);
- *Crowdsourcing* (see e.g. [26,100,7,61]).

As common properties of these systems and architectures, whether in CompSci or MS, could be identified as: (1) all of them are networked systems, integrating large numbers of "nodes", from thousands to billions! (2) all of them have extremely high capacity of changing the way of work and doing business, whether for individuals or for companies, and (3) all of them are highly scalable systems simply because these systems "are not bound to a predefined size, so that the underlying coordination mechanism has to be highly scalable" [156]. The scalability of these systems imply "solutions for huge networks/applications and support for global spontaneous interoperability" [150]. The common challenge are the "limitations of the current Internet architecture in terms of mobility, availability, manageability and scalability" [18], implying the requirements for designing automated discovery mechanisms, in order to achieve a scalable and accurate network management capability, high performance, scalable algorithms and protocols [18], for communication networks capable of self-healing, secured, efficient, interoperable, and based on open standards with plug-and-play capability [108].

As advanced instruments for the highest level of scalability achievements it is important to refer to the mechanisms for auto-scaling and automatic scaling of the systems. An example of a reference architecture for Transactional Auto Scaler (TAS) as an automatic elastic scaling system proposed by [54] is presented in Fig. 27.

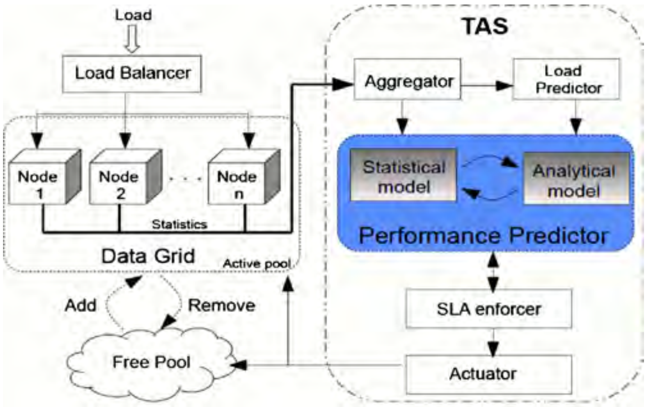


Fig. 27. Transactional Auto Scaler (TAS) reference architecture [54].

6.2. Manufacturing systems

The employments of GC, UC, IoT, CC, and Web in manufacturing systems, at the moment are primarily in support of information processing, but recently in other areas too, using 'smart object' technologies and components (building, or enabling, ubiquitous systems and 'Internet of things'), have originated new terms to designate the manufacturing systems that rely on these technologies, namely:

Ubiquitous Manufacturing (UM),
Grid Manufacturing (GM),
Cloud Manufacturing (CM).

Also, the terms Ubiquitous Manufacturing System (UMS), Grid Manufacturing System (GMS), Cloud Manufacturing System (CMS) could be used.

Paradigmatically, there are two models for employing the technologies and concepts of UC, GC and CC. These two models are fundamentally different, representing in fact two radically distinct paradigms of manufacturing systems:

- *The first paradigm* considers ubiquitous/grid/cloud manufacturing (U/G/CM) as a MS that *uses* ubiquitous/grid/cloud computing systems (U/G/CC), Fig. 28a.
- *The second paradigm* considers ubiquitous/grid/cloud manufacturing (U/G/CM) as a *homomorphism* of the ubiquitous/grid/cloud computing systems (U/G/CC), Fig. 28b.

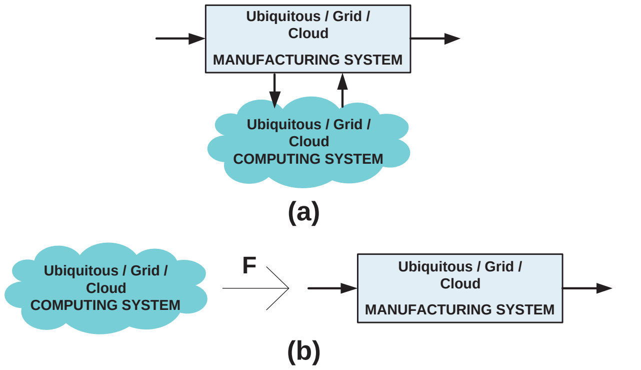


Fig. 28. Ubiquitous/Grid/Cloud Manufacturing (U/G/CM) when (a) using Ubiquitous/Grid/Cloud Computing (U/G/CC), and (b) is a homomorphism of Ubiquitous/Grid/Cloud Computing (U/G/CC).

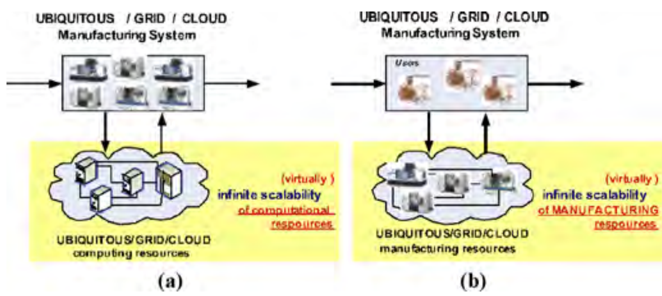


Fig. 29. Ubiquitous/Grid/Cloud Manufacturing with (a) virtually infinite scalability of computing resources when using UC/GC/CC, and (b) virtually infinite scalability of manufacturing, or, production resources as a homomorphism of UC/GC/CC.

The *first paradigm* is characterized by preservation of the actual manufacturing systems and enterprises' organizational paradigm and represents conceptually the actual organizational paradigm improvement or optimization through the new, more efficient, supporting computational resources, using, actually, UC/GC/CC as a specific company's new "operating systems", with, virtually infinite scalability of computational resources – to be used in any of the CIM/Digital Factory/etc. functions, Fig. 29a. Naturally, the use of new resources implies organizational changes but these are "improvements" and "optimizations" and "linear" in nature.

The *second paradigm* considers UM/GM/CM as a homomorphism of the UC/GC/CC, implying fundamental architectural, organizational and operational changes of the enterprises, i.e. implying the new organizations' intra- and inter-organizational paradigm, that enable the new organizations as the non-linear, "flow" organizations, capable to pass through the transformative changes. In this respect scalability is one of the fundamental features. The second paradigm offers *virtually infinite scalability of manufacturing productions resources* other than computing resources, Fig. 29b.

UM/GM/CM by the second paradigm do not have necessarily to use the UC/GC/CC but, could, and have to, do it to reach the highest level of performance by whatever criteria.

For the concept of UM a number of models and applications are already developed. Also, elements and some models of the concept are already implemented in industry too, mainly through implementation of embedded systems, RFID components and wireless sensors networks. Refs. [32] and [111] present UM model, designated u-Manufacturing, using RFID/USN technologies, including mobile and remote operation for M2M (Machine to Machine) implementation methodology.

In [110] the concept of UM is applied to "ubiquitous supply chain management", while in [127] UM is related to product life-cycle support.

Ref. [157] proposed a model of UM called "Person-Achieved Ubiquitous Manufacturing (PAUM)", and the model proposed by [180] is called "UbiDM (Design and Manufacture via Ubiquitous

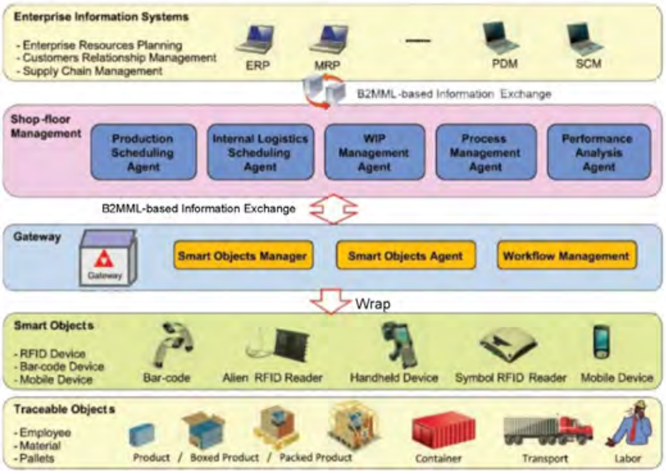


Fig. 30. Reference framework for UM [214].

Computing Technology)". In [211] a conceptual framework for the ubiquitous factory is presented.

In [213] and [214] the smart objects management system model for "real-time ubiquitous manufacturing" is presented. A reference framework for UM is presented as well, Fig. 30.

It should be noticed that all models and applications referred to above follow the first paradigm of UC applications.

Concerning the second paradigm, the phenomenon of UM has been known for a years although not as application of UC. Ref. [80] cites Alfred Weber's definition of ubiquitous manufacturing:

> "Ubiquity naturally does not mean that a commodity is present or producible at every mathematical point of the country or region. It means that the commodity is so extensively available within the region that, wherever a place of consumption is located, there are . . . opportunities for producing it in the vicinity. Ubiquity is therefore not a mathematical, but a practical and approximate, term (praktischer Naherungsbegriff)."

That is, "the term 'ubiquitous'" is "explicitly defined to be functional in an empirical context . . .The types of manufacturing which are both market oriented and have a frequency of occurrence greater than a specific limit which can be empirically defined are ubiquitous . . .". The importance of [80] work is in contributing to the understanding of the phenomena of ubiquity, and related scalability, and in that they may not need necessarily the UC technologies.

Grid manufacturing is also investigated by a number of researchers. Different frameworks are proposed, see e.g. [34,201,39,101]. Also, specific aspects of grid are investigated, e.g. in [173] modeling manufacturing resources as one of the key technologies of implementing GM is investigated, in [210] an agent-based Semantic Grid for distributed collaborative manufacturing is proposed.

In [215] a real-time simulation grid for collaborative virtual assembly of complex products is proposed, while in [162] a cost models are investigated for Micro Manufacturing logistics when using a Grid of Equiplets.

Ref. [163] refers to GM in the context of the 2nd paradigm of GC application.

Concerning the scalability of GM and of the GC application for manufacturing, it is explicitly mentioned in, e.g. [206] and [215], while in the majority of reports it is not.

An exhaustive overview of GM is presented in [184].

Concerning Cloud Manufacturing, the investigation at this time is focused on the concepts and architectures, e.g. [208] and [205], and, which distinguishes CM from other approaches, on servicizing the manufacturing systems processes, e.g. [35], and on resources allocation and resources and services scheduling, e.g. in [120]. In [121] the Collaborative Design Task Scheduling in CM is investigated.

The scalability issue is also explicitly referred to, as well as the CM that maps CC in terms of the 2nd paradigm of CC applications, see e.g. [208].

7. Selected epistemological aspects of scalability

7.1. *Relevance II – requirements for scalability in manufacturing systems design and operation*

Scalability is identified as one of the issues in a number of manufacturing systems contexts. It is related mainly to different forms of changeability, as [202], and to more detailed RMS, but also in the contexts of the co-evolution paradigm, that considers products, processes and production systems in co-evolution [187].

In [142] scalability is identified as one of two basic organizational requirements for SMEs, that forms federal supply chains as the dynamic structure of the SME production network. On the cooperation level it must be freely scalable, depending upon the mutual trust. In [147] scalability is referred to as one of the "fundamental issues of distributed manufacturing as agent structures". In [167], scalability is identified as "the major challenge for mechanical systems design optimization", particularly in the case of large-scale design due to high complexity.

Though not directly identified as strong requirement, scalability is important for concepts such as "cooperative and responsive manufacturing enterprises" [194]; "Industrial Product-Service Systems-IPS^2" [143]; "agent-based production planning and control" [185]; "monitoring of manufacturing operations" [186].

This is because cooperative, and furthermore collaborative, distributed systems might benefit from scaling the groups, and activities such as servicing and monitoring manufacturing processes, machines, systems and products should consider scalability in terms of business development as well as in terms of supporting technology and business models. Cloud Manufacturing is exactly a form of virtually totally serviced manufacturing system.

7.2. *Scalability as an organizational, business and social issue*

The importance of scalability in business and social systems is manifested through different dimensions. These are human resources, business success and growth, firm's value creation potential, social entrepreneurship, and others.

The workforce scalability is "a requirement of organizations operating in a dynamic environment [56]. Workforce scalability refers to 'the capacity of an organization to keep its human resources aligned with business needs by transitioning quickly and easily from one human resources configuration to another and another, ad infinitum". There are "two dimensions of workforce scalability – alignment and fluidity".

In [41] scalability is identified as "a critical factor for the success of business, commerce, and entertainment across the Internet, and it is a problem that attracts, perhaps, the most amount of attention among Internet and WWW infrastructure issues".

Ref. [136] identifies that "both scalability and flexibility become important drivers of the R&D process in India, the possibilities for Indian firms to gain shares in domestic and global markets becomes high"

Ref. [10] confirms that "the firm's value-creating potential can be enhanced through scalability (i.e., increasing the number of transactions that flow through the e-business platform)." But also, "The choice of transaction structure influences the flexibility, adaptability, and scalability of the actual transactions".

Ref. [140] defines scalability of an organization as "the ability of an organization or movement to grow its resources, operations, and influence beyond the scope of origin." Furthermore, "Social entrepreneurs move beyond existing social structures by employing innovative strategies that if successful lead to sustainable and scalable social transformation."

Additionally, specific contributions to the social dimension of scalability exploration, enabled by the new paradigms (computational and manufacturing organizations), are the low cost alternative to the company's internal manufacturing processes, such as, e.g., quick prototyping and scalable/flexible novel services, enabled by Cloud computing and other technologies, useful for early stage start-ups. For example, some of the "specific chances" created by the development of cloud technology are [170]: (1) new business models and expert systems; (2) holistic management and control systems; (3) mediation of services and applications on cloud; (4) start-up networks; (5) quick prototyping; (6) scalable/flexible novel services.

7.3. Requirements for scalability in education

There are three dimensions of the scalability issue in education:

1) Scalable education.
2) Use of scalable technologies for education.
3) Education of scalability.

Scalable education

Scalability of education has its best manifestation through the concept of e-learning. In [37] scalability is one of the e-learning's "vital principle", as "e-learning can be scaled almost infinitely at little additional cost".

One of the most important, and "exiting", effects of e-learning is that it "stimulates" "strategic alliances ... between giant technology and media companies, leading international universities, and enterprising new e-learning companies" creating "e-learning environment ... of immense influence and penetration" [37]. The concept has motivated "galaxies" of start-up companies that virtually all have "abandoned the formal names of education and training, and replaced them with a sense of the immediacy, speed and universality of the world of new technology, with obligatory references in company names to global, knowledge, planet, network, digital, and brain" [37].

It is important to mention that the scalable education, in its e-learning form, relies on scalable technologies [37].

In [164] the project on "Scalable Game Design Initiative" is proposed. "The essence of Scalable Game Design is that programming challenges and skills should be balanced and there are different paths, some better suited than others for broadening participation".

Ref. [109] indicates that "government, industry and corporate users are increasingly focusing on standardization issues and the scalability of technology platforms to meet demand." In this context, the example of "The University for Industry (UfI) in UK, is referred as "the most impressive demonstration of scalability in terms of raw numbers" [109,181].

Furthermore, The World Bank Institute (2004) defined a list of challenges for e-learning that includes scalability, and shareability, in terms of needs "for standards that promote the sharing and scaling up of e-learning assets" [109].

Use of scalable technologies for education

The employment of cloud computing platform and SaaS [81], makes the students "deploying their projects in the same horizontally scalable environment used by professional developers is instant, free for small projects, and requires neither software installation nor joining a developer program. In particular, it frees the course from instructional computers, which are often antiquated, overloaded, or both." Additionally, "using the cloud to teach the class" provided the "students the chance to experiment with scalability".

In [86] the scalability performance aspects of e-learning oriented Web Services are investigated.

Education of scalability

Education of scalability is a regular issue in CompSci courses, especially within the courses on advanced computer architectures, e.g. [105]. Also, the scalability issues of specific applications are taught, e.g. in [104] "the basics for a reusable, scalable and adoptable simulation models", and "an implementation of a training game based on such a model" are discussed.

Finally, of our highest interest is education on scalability in manufacturing systems.

ElMaraghy et al. [59] presented a survey on "learning factories that possess attributes of changeability", and the use of scalable and changeable manufacturing systems in research and education about scalability and product variety management. Learning factories at more than 20 leading research and development organizations were surveyed.

The survey showed that the scalability is addressed in different forms, such as:

- "by Plug n play elements of the system modules",
- "mobile system modules and system layout and configuration variants",
- "RFID and mono rail system ... built up on a modular basis",
- "standardized equipment components and interfaces (physical, energy and information)".

7.4. Some industrial applications

This section presents scalability applications, or implementations, in manufacturing companies' "real-life". It is presented as a qualitative, rather than a quantitative, overview of the scalability implementations, based on extensive (yet virtually not "complete") literature review as a direct survey of the industrial companies was not within the scope of this paper due to the available space.

Manufacturing systems architectures

No 'explicit' solutions/implementations are found for MS generated by the "scalability theory", with the exception of RMS, but implementations based on earlier solutions referring to flexibility (flexible manufacturing systems – FMS) rather than scalability itself, meaning that solutions are scalable per se, i.e. 'implicit'. This is the case of e.g. modular reconfigurable Flexible Assembly Systems (FAS) [97] when scalability is not referred to as the design goal but rather the operational flexibility by designing the system using modules.

Other referencing of industrial systems scalability is through the analysis of the scalability of existing systems, e.g. [119] or through experimental verification and validation in industrial settings. It is possible to say that formally any existing industrial "real-life" system is scalable to some degree, see Section 3.2 (the lowest "end" is scalability equal to 0), and therefore it might be an object of the survey. However, these systems will be not referred to, but only the systems that are intentionally developed as scalable, or employing scalable technologies defined in previous sections.

An example of industrial application of RMS is given in [47], for a "computer peripherals automatic assembly line (mother boards, VGA cards, sound cards, memory cards and fax modem cards). The capacity is scaled up by adding two extra pick and place machines in series.", as shown in Fig. 31.

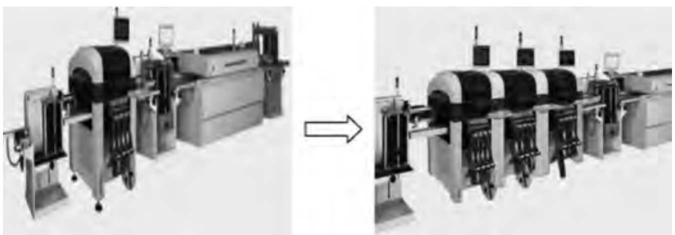


Fig. 31. An industrial application of the capacity scalability at the MS level [47].

Although the system per se is based on, i.e. could be considered as, a modular reconfigurable FAS, it is a consequence of a "systematic design approach for reconfigurable MS", implying adding and removing the pick and place machines, and, therefore, could be considered as the explicit application of scalable MS.

As further examples of the scalable MS architecture models the present industrial implementations of ubiquitous or cloud manufacturing systems could be considered as well. It should be noticed that these implementations do not have scalability implemented on the manufacturing system level in the strict sense, i.e. on the level of manufacturing equipment, workshops and process, but they have implemented scalability on the supporting ICT architectures, which could also be interpreted as the parts of an overall MS architecture. However, the examples of these implementations will be presented below within the section 'MS ICT supporting technologies'.

Manufacturing systems hardware/equipment

Industrial examples are, again, related to Reconfigurable Machine Tools (RMT) [113]. A typical example developed at the NSF Engineering Research Center for Reconfigurable Manufacturing Systems at University of Michigan is a model of *Archtype RMT*, Fig. 32 [52].

Another example of industrial application is the *Reconfigurable Inspection Machine* [114], developed by the same center, and implemented at a GEMA (Global Engine Manufacturing Alliance) plant, and in the GM Flint plant, Fig. 33 [62].

Fig. 32. Archtype RMT [52].

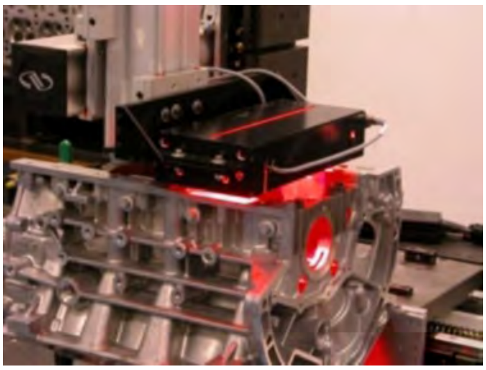


Fig. 33. Reconfigurable Inspection Machine in use [62].

In [47] (already mentioned above) there is also reference to the case of RMT, for the same case of the "computer peripherals automatic assembly line . . .", Fig. 31.

Manufacturing systems ICT supporting technologies

Examples of industrial implementations of scalable MS ICT supporting technologies are based on implementation of the ICT technologies with already proven scalability. These are, in the first place, Ubiquitous Computing (UC) and Cloud Computing (CC) based implementations. In the context of ubiquity, the hardware components implemented are different types of sensors, communication modules and so-called "smart-objects". Concerning Cloud Computing based implementations, these technologies are implemented as support for data storage systems as well as service systems in the context of production planning and control functions.

An example of ubiquitous systems implementation is from a water turbines manufacturer's factory, for the case of monitoring the welding stations clusters. Fig. 34 presents (a) the logical architecture, (b) the workshop view with one of the controlling terminals implemented [125] and [126]. The implementation is realized under the EUREKA and 'The Foundation for Science and Technology – FCT' project on 'Ubiquitous oriented embedded systems for globally distributed factories of manufacturing enterprises'.

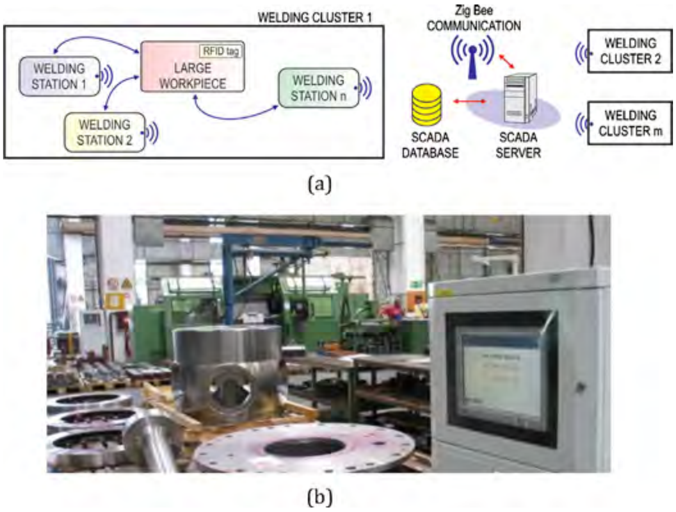


Fig. 34. Ubiquitous Computing based monitoring of the welding stations clusters: (a) logical architecture; (b) workshop view with the controlling terminal in the first plane [125].

Other examples of the ubiquitous systems implementations are from Korea. In different manufacturing factories, ubiquitous systems are implemented for production monitoring and control and the corresponding cloud-based service systems [33]. Fig. 35 shows the architecture and different hardware components and terminals of the implemented systems.

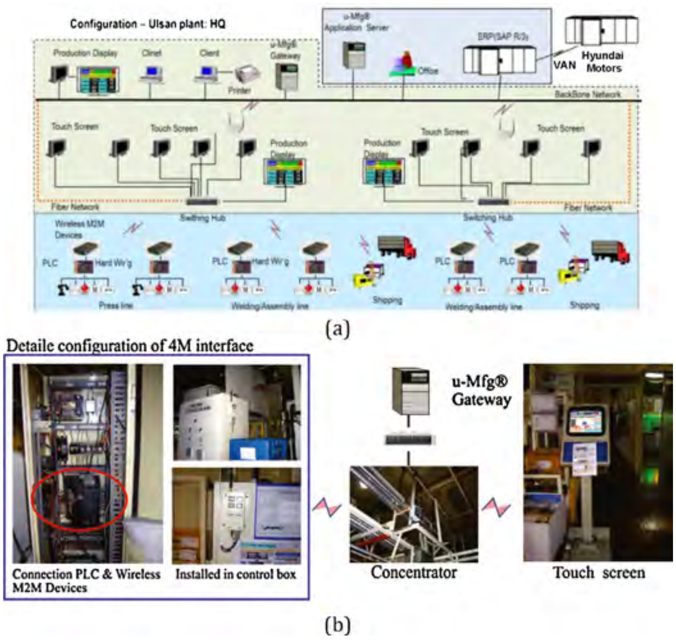


Fig. 35. u-Manufacturing implementation (a) logical architecture; (b) hardware components implementations [33].

Parallel architecture and parallel processing for the operational history storage, as an example of a scalable storage system, is implemented in the case of remote monitoring and maintenance system for CNC machine tools services by a machine tool company, for the purpose of incoming emails processing at the rate of approximately 500 requests/day [148], Fig. 36.

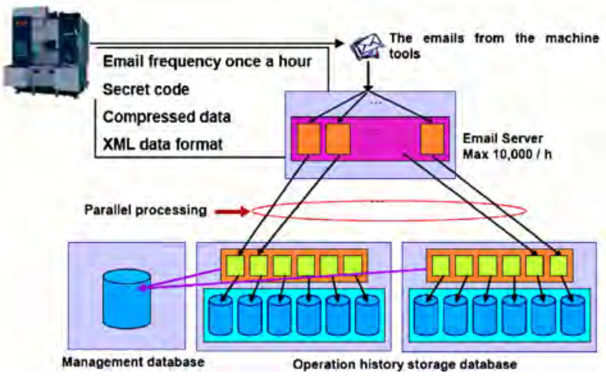


Fig. 36. Parallel processing of incoming emails [148].

Scalable architectures are also a basis for numerous products in the area of manufacturing control/automation systems. For example, scalable Programmable Logical Controllers (PLC) for various types of controls, including controlling equipment multiple "axis", etc. Examples of Siemens's SIMATIC TDC – "Modular system structure with scalable hardware – also for the largest and most complex applications" with capacity of "synchronized multiprocessing with as many as 20 CPUs per rack and synchronous coupling of up to 44 racks", SIMATIC FM 458-1 for "high-performance motion control" with "scalable number of controlled axes (more than 100 axes possible)" and SIMATIC PCS 7 as a control system with "a unique scalable architecture" for "seamless integration" of "the plant-wide automation and information architecture", with up to 120,000 I/Os, SIMATIC IT Manufacturing Execution Systems as a modular and scalable concept, scalable SCADA system ("from single-user systems to distributed SCADA systems with redundant servers", "up to 2048 servers on distributed systems, … scalable up to networked redundant high-end systems with more than 10 million tags), etc. [174].

8. Toward a roadmap for scalability theory and practice development

A roadmap is a technology management instrument. It serves a number of purposes, ranging from e.g. product and process planning to strategic and long range planning [159], including forward-looking policy design [4], technology foresight [19], as an infrastructure for innovation [165], for business and technology integration [89], as an instrument for "systemic transformation, anticipatory culture, and knowledge spaces" capacities development [5].

When it serves as a planning instrument it necessarily represents a time-based mapping between "technological resources, organizational objectives and the changing environment" and their "dynamic linkages" [159].

However, road mapping is seriously challenged by the nowadays dynamics of our environment (by whatever parameter). In accordance with different emerging management and designing disciplines such as "chaos and complexity management in organizations", and "co-creation" approach (the "co-creation" discipline promotes in fact social construction, which is, by its nature, context dependent), as new paradigms to inform modern design and management, any planning is virtually impossible as a controlling instrument. The limitations of road mapping in dynamic environments has been perceived and in order to overcome them traditional roadmaps are combined with other instruments, such as scenario planning [179].

In other words, considering scalability road mapping, it is not reasonable to expect that any "prescriptive" roadmap, in terms of developing "timetable" can be effective when challenged by the dynamic, uncertain, or complex environment. Instead, "planning" has more a role of providing visions and individual and collective learning, rather than prescriptions.

Considering scalability in manufacturing systems, it means that the roadmap for scalability should provide a foresight, rather than forecast, for scalability research, development and implementation. For its presentation a "text" format is chosen, just to avoid "prescriptive" contents which would ignore the need for dynamic "co-creation" along the time.

The roadmap for scalability has the purpose to ultimately incentivise exploration of scalability in a number of dimensions. To achieve it the research should address as well the theory of scalability, which immediately establishes an "ordering" of activities on scalability research, development and implementation.

The Scalability Roadmap could be structured around five global research challenges:

1. Theory of scalability for MS (see Box 8.1).
2. Scalability for the actual MS paradigm (see Box 8.2).
3. Scalability for emergent MS paradigm(s) (see Box 8.3).
4. Business and social dimension of scalability (see Box 8.4).
5. Scalability Roadmap through the lenses of emerging and challenging fields in CIRP STC O.

Box 8.1. Research Challenge 1: Theory of scalability for Manufacturing Systems (MS)

Description

The problems that are expected to be resolved, or further improved, by scalability theory development, are:

- development of advanced, improved and new scalability models, mechanisms of choice (incl. management), and instruments for the actual and emerging MS paradigms;
- effective and efficient implementation and use of scalability instruments;
- effective and efficient management of scalability and management of scalability instruments development and implementation;
- effective and efficient transfer of knowledge on scalability among the disciplines, Unified scalability theory and models across different disciplines and application areas;
- introduction of, and contribution to building a *norm* of, "scalability" as a new "performance measure" in MS design, management and operation.

Research activity

1.1. Extending the scalability domain by optimization of the available and new scalability instruments, Fig. 37.
1.2. Increasing return creation through scalability (scale out) – based on network effect, Fig. 38.
1.3. Unified theory of scalability–abstracting differences between MS and CompSc.
1.4. Meta-scalability – scaling integration of different types and magnitudes of scalability–related to increasing return.
1.5. Meta-scalability – scaling integration of different types and magnitudes of scalability – related to "seamless technological chain from nano- to macro-" (after [51]).
1.6. Scalability models and performance measures – scalability capacity of MS architectures, equipment, tools, processes by costs, economy, trust, and other criteria, in terms of Amdahl's Law, Gustafson's Law and Universal Scalability Law (USL) parameters, and in terms of "economic scalability".
1.7. Scalability models and new performance measures – related to increased return, social effects and meta-scalability, in terms of Amdahl's Law, Gustafson's Law and Universal Scalability Law (USL) parameters, and in terms of "economic scalability".
1.8. Alternative scalability laws for specific cases and manufacturing systems models.
1.9. Design for scalability – in terms of solutions for the scalability "inverse problems", i.e. designing systems for given scalability requirements.
1.10. Mapping scalability concepts and instruments from CompSc to MS.
1.11. Mapping scalability formal models from CompSc to MS.
1.12. Scalability in heterogeneous environments.
1.13. Terminology unification.

Box 8.2. Research Challenge 2: Scalability for the actual MS paradigm

Description

Development of scalability models, mechanisms of choice (incl. management), and instruments for the actual MS paradigms.

The problems that are expected to be resolved, or further improved, by scalability instruments implementation, along the scalability research, development and implementation, are:

- reducing the Time-to-Market (TTM), through launching operations on parallel resources, along the whole product development life-cycle, and, consequently, increasing competitiveness by TTM reduction;
- employment of available equipment and other resources through scalability management;
- exploration of capacities of new emerging manufacturing systems concepts such as Industrial Product-Service Systems (IPS^2), and Collaborative and Co-Creative design, management, organizations and environments;
- contributing to faster realization of the environmental sustainability policies by faster launching and adoption of ''eco-friendly'' products, how the scalability models can be applied for different specific cases.

Research activity

2.1. Scalable machine tools (MT)/manufacturing systems (MS) architectures and components.
2.2 Management for scalability and performance measures – scalability of design resources, process planning for scalable production, management of production in scalable MS, scalable quality control.
2.3. Scalable management for design resources, process planning, production planning, production control, quality control, etc.
2.4. Scalable decision-making – design, process planning, production planning, production control, as a form of co-creative design, planning, control.
2.5. Simulation tools – for scalability and scalable simulation tools.
2.6. Design and use of scalable reconfigurable manufacturing systems in education such as learning factories.
2.7. Meso- and micro-MT of very low cost – target price 50€ – from reusable components, from wood and/or plastic.
2.8 Meso- and micro-MT further minituarization – e.g. for maintenance and repair within the MT (*scale up/down* – scaling size parameter of MT).
2.9. Scaling integration of equipment and systems over different magnitudes of scale – providing ''a seamless technological chain from nano- to macro-'' [51].
2.10. From ego-centric to poly-centric companies – related with increased return and emergence (base for co-creative company).
2.11. Semiotic based company – related to co-creation.
2.12. Scalability ''de-facto'' standards – co-creation of standards, interoperability – dynamically reconfigurated (standards).
2.13. Design for scalability – as a direct problem solutions.
2.14. Design for scalability – as an inverse problem solutions – scalability theory application for generation of scalable MS.
2.15. Business models for scalable MS – PSS related.
2.16. Scalable environments for MS – for digital and virtual manufacturing systems and enterprises.
2.17. Scalability for agility and leanness in dynamic co-existence.
2.18. Cost effective scalability models in the context of the ''economic scalability''.
2.19. Management of organizational slack as the scalability resource.
2.20. Massive and large-scale use of scalability in MS.
2.21. Reduction of the TTM and adoption time of eco-friendly new products and equipment through massive use of scalability and/or scalable MS, in order to significantly reduce the time for achieving the GHG emission goals [70], Fig. 39.
2.22. New application areas.
2.23. Scalability cost/economic models & expertise.
2.24. Scalability of heterogeneous systems.
2.25. Scalability disablers.
2.26. Scalability modalities.
2.27. Scalability usage specific behavior.
2.28. Scalability migration policies and procedures.
2.29. Scalability effort analysis in terms of complexity and timescale.
2.30. Fast transitions to scalable MS.

(*Note*: 2.23-2.30 inspired by [171])

Box 8.3. Research Challenge 3: Scalability for emergent MS paradigm(s)

Description

The goals that are expected to be achieved concerning scalability, seeing the scalability as the new potential, the new capacity, the new resource for, and in, ''emergent'' MS paradigms, are:

- further improvement of the performances of the actual MS paradigms, by employment of growing capacity of computational resources of new computational technologies and paradigms such as Cloud Computing (CC),Ubiquitous Computing (UC), Grid Computing (GC), Social Networks (SN), Internet of Things (IoT), and others;
- creation of new capacities and possibilities for new emerging manufacturing systems concepts (including e.g. Industrial Product-Service Systems (IPS2), and Collaborative and Co-Creative organizations and environments);
- creation of new capacities and possibilities for emergence of new businesses;
- creation of new capacities and possibilities for social objectives such as employment, sustainability, education, and others.

Research activity

3.1. Large-scale architectures of UM, GM, and CM.
3.2. Open architectures development of UM, GM, and CM.
3.3. Open architectures development for UM, GM, and CM.
3.4. Exploration of crowdsourcing, Web 3.0 and 4.0, social networks, organizational slack.
3.5. Design, production planning and production control in UM, GM, and CM.
3.6. Performance measures of design, production planning and production control management in UM, GM, and CM.
3.7. Meta-organizations for UM, GM, and CM.
3.8. Knowledge transfer to, from and between UM, GM, and CM.
3.9. Data management and handling in UM, GM, and CM.
3.10. Resource awareness in UM, GM, and CM.
3.11. Multi-tenancy impact and management in UM, GM, and CM.
3.12. Programmability for UM, GM, and CM.
3.13. Network management of UM, GM, and CM.
3.14. Legislation and policies for UM, GM, and CM.
3.15. Scalability cost/economic models & expertise for UM, GM, and CM.
3.16. Business models for UM, GM, and CM.
3.17. Scalability of heterogeneous systems of UM, GM, and CM.
3.18. Scalability disablers for UM, GM, and CM.
3.19. Scalability modalities for UM, GM, and CM.
3.20. Scalability usage specific behavior for UM, GM, and CM.
3.21. Scalability migration policies and procedures for UM, GM, and CM and from actual MS paradigms.
3.22. Scalability effort analysis in terms of complexity and timescale for UM, GM, and CM.
3.23. Fast transitions to scalable UM, GM, and CM and between.
3.24. UM, GM, and CM ecosystem.

(*Note*: 3.9-3.24 inspired by [171])

Box 8.4. Research Challenge 4: Business and social dimension of scalability

Description

The goals that are expected to be achieved by scalability instruments implementation and use concerning business and social dimension, are:

- using scalability as the new potential, the new capacity, the new resource for the business and social developments;
- improvement of social sustainability, employment, inclusion, education, innovation, autonomy and self-organization.

Research activity

4.1. Scalable access to knowledge.
4.2. Scalable education, pedagogy, tools and modules.
4.3. Education of scalability – for scalable and scalability of MS.
4.4. Employment of available human resources through scalability management and new emerging manufacturing systems concepts, which addresses the social dimension.

4.5. Eentrepreneurship promotion and development through organizational scalability initiatives.
4.6. Innovation promotion and development through organizational scalability initiatives.
4.7. Rapid businesses growth.
4.8. Rapid transfer from laboratory scales to industrial scales.
4.9. New business models.
4.10. Increasing competitiveness.
4.11. Increasing collaborativeness.
4.12. Taxonomies and quantifications of products and competencies (HR) adequate for scalability.
4.13. Easier access of SMEs, micro-enterprises, and individuals to scalable resources and participations in scalable MS.
4.14. Ensuring progress in scalability research.
4.15. Adoption of organizational and social scalability.
4.16. From industry driven scalability to co-existence with Driving industry & society.

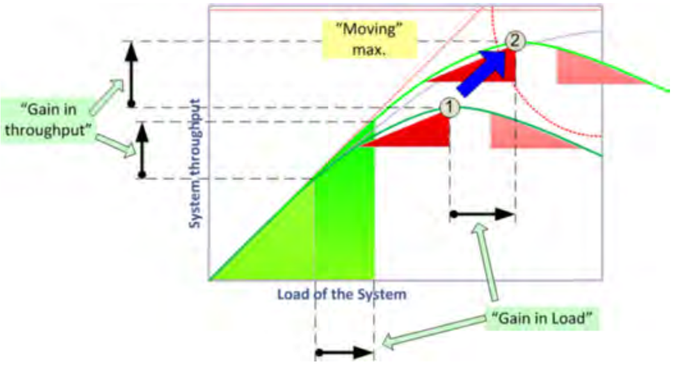


Fig. 37. Extending the scalability domain.

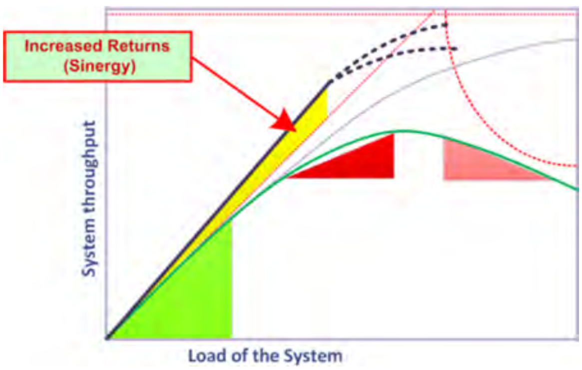
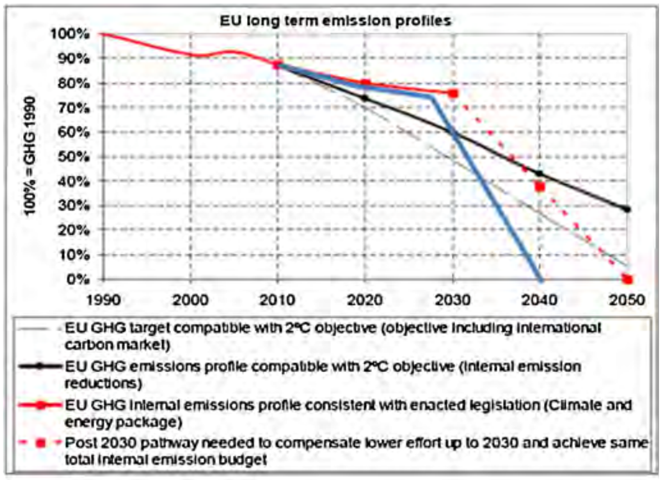


Fig. 38. Increasing return creation through scalability (scale out) – based on network effect.



Source: POLES,PRIMES, GAINS

Fig. 39. Short term EU emission profile compared to 2 °C compatible long term target (p. 41) [70] and achievable "time-line" (in blue).

Research Challenge 5: Scalability Roadmap through the lenses of emerging and challenging fields in CIRP STC O

Concerning the CIRP community, the question of the Scalability Roadmap could be seen through the lenses of the continuous discussion within the CIRP community on the question of emerging and challenging research directions for the future. Following [191,192], emerging and challenging fields in CIRP STC O are mainly the so-called Classes II and III problems, and relying on co-creative approaches, Table 3.

In other words, for facing emerging and challenging fields, the STC O related research necessarily has to pay much more attention to, "move" toward, or include more, social aspects and social issues of technology. This is absolutely necessary considering the strategic objectives of creating a sustainable society.

Concerning scalability, one of the global research challenges is exactly the social dimension of scalability, implying application of co-creative approaches and methodologies for value creation on the "axiological" level and co-creative based design and management on the operational levels.

On the other hand, the question is what the role of scalability in this scenario is. This question is just another form of the fundamental question on scalability concerning co-creative methodologies:

Table 3
Classified activity phases and extension of CIRP-O activity.

Emerging and challenging research fields for the future research in STC O [191,192]	Activity phase	Field	Scalability
Emerging fields in CIRP-O			
Classification: Class II Incomplete environment information problem	Standardization	Simple De Facto Standard	X
	Innovation	Collaborative Open Innovation	X
	Business model	Adaptive type	
	Value creation model	Adaptive Value	
Classification: Class III Incomplete Purpose information Problem	Research Problem Type	Co-creative solution coupling with objective definition	X
	Product	Co- creation type	X
	Process/Service	Co-creative Process (Interactive production, Co- creative service)	X
Challenging fields close to CIRP-O			
Classification: Class III Incomplete Purpose information Problem	Standardization	Co-creative De Facto Standard	X
	Innovation	Co-creative Open innovation	X
	Business model	Co-creative type	X
	Value creation model	Co-creative Value	X

How scalability of the groups and/or communities affects the co-creation effectiveness and efficiency.

Which, in fact, represents the main research challenge concerning scalability, co-creation and the CIRP-O emerging and research challenges toward sustainable society.

9. Conclusions

Scalability of systems, and in our particular case of manufacturing systems, could be seen as a system's feature that might provide a significant increase of potentials for resolving a number of problems in manufacturing systems design and operation and for *enabling new visions*, whether quantitatively or qualitatively.

In other words, manufacturing systems scalability might provide further optimization of the manufacturing systems design and operation or enable the development of paradigmatically new manufacturing systems for the sustainability and wellbeing society. Besides the functional aspects of scalability, which could be seen as primarily technical issues, by considering the wider social concerns the scalability feature might also be seen as an instrument for value increase (following requests for value creation and sustainable society, see [190]).

Scalability modeling and applications are widely considered in an ample range of application areas, with special success in CompSci and, conditionally speaking, virtually initial success in MS. The question is whether scalability deserves, and whether it would be useful, to be considered as an emerging discipline? In accordance with [2], "One of the missing disciplines is the scalability architect". They wrote also: "One of our most-commented-on blog posts is on the need for scalability to become a discipline. We and the community of technologists that tackle scalability problems believe that scalability architects are needed in today's technology organizations".

Another scalability issue that could be emphasized in conclusions is the social dimension of scalability, i.e. its possible impact on social issues such as innovation, employment and economic development. By [195]:

"Scalability of manufacturing is what creates employment, drives innovation and propels the economy."

This is exactly what could be the final message in presenting the issue of scalability and in its promotion in manufacturing systems design and operation.

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