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A systemic criterion of sustainability in agile manufacturing

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Abstract. Agile manufacturing systems work in a constant change in a global market, in particular, assembly systems at the last stage of product differentiation. Meanwhile, sustainability is becoming a key issue for manufacturing strategy. This paper formulates a systemic criterion of sustainability in agile manufacturing and computes it through flexibility and complexity. It is defined a ratio of utility and entropy as a sustainability measurement. Under a unified framework, utility allows to quantify the contributions to agility, in particular system flexibility. Complexity is measured by entropy. Thus, it is proposed an original complementary role of flexibility and the complexity of the system. Developed from the distribution of system states, the systemic approach to sustainability in terms of output evolution is enriched. Based on a simple assembly line integer model simulation, a first quantitative analysis illustrates the concepts introduced.

Keywords: agility manufacturing, decision support systems, complexity, flexibility, sustainability

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1. Nomenclature

C_r reduced cost, in the hybrid lines assembly model.

F flexibility.

H system entropy, metric of system complexity.

H_s structural complexity by Frizelle and Efstathiou (2002).

O_t output vector evaluated at *t*, in Gallopin (1996) sustainability definition.

p_{ij} probability of resource (machine or line) *i* being in state *j*.

Q_r reduced quality, in the hybrid lines assembly model.

S, S(x) sustainability, sustainability as a function of a state variable.

v utility value (Calvo *et al*. 2003), utility prospect of a utility vector (Abbas 2006)

v(x) density function of the probability distribution *V(x)*.

V, V(x) expected utility or valuation (sustainability definition), cumulative distribution function of utility to respect the *x* state parameter.

ΔV utility-increment vector.

Δv_i discrete utility increment, *i* element of the discrete utility-increment vector ΔV.

ΔV_j discrete utility value. Correspond to the component *j* of the utility-increment vector.

T_r reduced delivery or makespan of the daily production.

t time.

x, x_t scalar state parameter, state parameter at the time *t*.

$x_1, x_2, \ldots, x_n$ scalar state parameters, variables that define productive factors.

2. Introduction

Nowadays manufacturing systems have to respond to continuous changes and sustainability requirements. Agile manufacturing has been identified as a broad concept to face it. Based on flexibility and the response to customer, agility also includes cost reduction, high quality of products and the delivery conditions and service (Goldman and Nagel 1991). Moreover agile manufacturing is a response to complexity brought about by constant change (Sanchez and Nagi 2001). Therefore, we find two relevant features of agility: flexibility and complexity. Flexibility has been identified as a key productive factor for success or competitive advantage (Suarez *et al*. 1995). It is required to handle a high variety of products. However, the variety of products increases the complexity (Wiendahl and Scholtissek 1994). Thus, complexity in a manufacturing system plays a counter-weighting role in the use of flexibility. Conversely, we live a trend towards an increasing product variety in a product life-cycle framework, including the evolution of manufacturing reorganisation towards simplicity, sustainability and the dynamic flexibility of subsystems (Wiendahl and Scholtissek 1994). Beyond the analysis of product end-of-life, a reference point is to consider sustainability from system capacity of maintaining performance under acceptable standards.

According to Alford *et al*. (2000), an effective approach must be developed to support decisions in order to promote customisation, but preventing complexity in manufacturing. We extend this approach to reach system sustainability. Some metrics have been given to flexibility assessment (Filippini *et al.* 1998, Ward *et al.* 1998, Calvo *et al.* 2003, Domingo *et al*. 2005), complexity (Deshmukh *et al.* 1992, Frizelle and Efstathiou 2002, Calvo *et al*. 2006) and sustainability (Gallopin 1996, Wall and Gong 2001).

However, literature lacks in providing an integrated metric. The original contribution of the paper includes formulating a criterion of sustainability in agile systems and quantifying its measure though flexibility and complexity.

We adopt the utility theory (Keeney and Ruiffa 1976) to quantify of flexibility. Authors have taken this approach (Calvo *et al*. 2003), using it in other manufacturing systems (Domingo *et al*. 2005, Calvo *et al*. 2006). Utility for the decision-maker allows quantifying the contributions of productive factors to agility. This theory permits to consider that the factors (e.g. cost, quality or delivery) are mutually preferentially independent. This is of a particular interest and easy application in industrial manufacturing systems. The complexity is measured by means of entropy by Frizelle and Efstathiou (2002). We proposed an original complementary role of flexibility and the complexity of the system. In this sense, entropy represents an estimation of uncertainty level. In addition, this paper takes in account the classic systemic sustainability by Gallopin (1996), but developing a new systemic approach to sustainability in terms of output evolution from the distribution of system states. Sustainability involves the ability to generate variety in a dissipative process that admits a decrease of entropy. It is proposed the ratio of utility and entropy as a sustainability measurement, interesting for the dynamic evolutions of agile systems.

3. Quantification of flexibility in manufacturing systems

Flexibility is the main differential productive factor of agility, compare to former manufacturing systems. Moreover, it is countermeasure against uncertainty. Nevertheless, most of the success assigned to flexibility could have been actually got through flexible technology, instead of a flexible management of the system. Consequently, the provision of flexible manufacturing systems (FMS) could not currently be enough to face scaling uncertainties. Manufacturing flexibility should be considered as a strategic and operative factor of production for decision-making (Hill and Chambers 1991). Therefore, it must be tightly integrated in the assessment of system performance along cost, quality and delivery. In their literature review about manufacturing flexibility, Beach *et al.* (2000) indicate that flexibility definitions include two common features: Response to change and uncertainty. The change of flexibility can be expressed as a short-term or a long-term operative decision. In this process, uncertainty can be managed to avoid negative impacts, or to improve system performance through strategic planning.

Flexibility quantification has not consolidated a group of measures widely accepted. The attempts to formulate a consistent generic schema of flexibility types and measures have had a limited success. Flexibility quantification cannot be independent from the performance measures, in particular in agile, complex and dynamic systems (Grubbström and Olhager 1997, Filippini *et al.* 1998, Ward *et al.* 1998). Decision-making can determine a radically opposite system behaviour, proper of complex systems evolution under different initial conditions. So, the compatibility between the strategic and the operational use of flexibility should be determined directly by the time scale and the outstanding parameters of the system. Therefore, a flexibility generic measure should allow including every relevant feature of the system for decision-making, in order to be a concept applicable to different manufacturing systems.

Decision-maker preferences can be introduced by the utility theory. A structure of priorities among different contributions to the utility is quantified by this function, and the objective of maximum utility is pursued to get the better combination of factors: Cost, quality and delivery. They can be considered mutually preferentially independent, so the level of each one does not depend on the level of the rest in the structure of decision-maker preference (Keeney and Ruiffa 1976). This assumption can be maintained since they represent complementary concepts. Although, the operative management of cost, quality or delivery is based on tradeoffs between them, because productive factors interact through the group of significant magnitudes that define the system state. The mutual preferential independence among factors facilitates the formulation of the utility function. Each mutual independent contributor can be aggregated as an additive function into the complete utility expression. The coefficients of each additive function can be interpreted as the scale factor or weights in the contribution of each factor. Every factor has its own unit of measurement, so in order to aggregate those different effects into the same function; it is proposed the addition of each contribution dimensionless. That is, dividing cost, quality and delivery contributions into significant reference values of the system. For sustainability purposes, environmental issues in decision-making can also be included in the utility function through its parameters of influence. In the operational field could include energy consumption, cost of recycling or disposal, costs of emission rights, etc. In a strategic perspective, the intangible values of a responsible and clean integration of activities can be evaluated through new metrics (Funk 2003).

In this approach, manufacturing flexibility, F, can be defined as the temporal ratio of incremental utility between two states (Calvo *et al*. 2003). Equation (1) quantifies this definition.

$$F = \frac{\Delta v}{\Delta t} = \left. \frac{\Delta\ v\,(x_1, x_2, \ldots\ , x_n\ )}{\Delta\ time} \right|_{state1}^{state2} = \frac{v_2 - v_1}{t_2 - t_1} \qquad (1)$$

The utility function, *v*, depends on productive factors and represents the structure of choice and trade-offs for the decision-maker (Keeney and Ruiffa 1976), by equation (2).

$$utility = v(cost,\ quality,\ delivery) = v(x_1, x_2, \ldots, x_n) \qquad (2)$$

Noted $x_1, x_2, \ldots, x_n$ as the scalar state parameters, they are the set of metrics that define a system status. Reminiscent from the theory of control, they are among the variables of the function of transference for system control. They can frequently take only integer values, e.g. product-to-line assignation. Discrete variations on manufacturing systems could be considered in an approximation under a continuous analysis by taking average values in convenient time intervals. So the utility function could be rewritten as a function of the state parameters of the manufacturing system

$$F = \frac{d\,v}{d\ t} = \frac{d\ v\,[x_1(t), x_2(t), \ldots x_n(t)]}{d\ t} = \frac{\partial v}{\partial x_1} \cdot \frac{d\,x_1}{d\,t} + \frac{\partial v}{\partial x_2} \cdot \frac{d\,x_2}{d\,t} \ldots + \frac{\partial v}{\partial x_n} \cdot \frac{d\,x_n}{d\,t} \qquad (3)$$

This definition quantifies production flexibility as the result of a change in the system and it can cover most of the metrics applicable to an agile manufacturing system. A positive variation of utility yields positive flexibility. Null flexibility corresponds with an interchange of productive factors, keeping overall utility. A negative evolution of utility yields negative flexibility. Flexibility is compatible with negative and positive evolutions, allowing the conciliation of two controversial aspects in manufacturing systems: World-Class Manufacturing efforts of agile manufacturing and the productive factors interchange. While the first one requires a positive change of flexibility, the second one is represented by evolutions of null flexibility. Moreover, this definition of flexibility permits the mathematical and conceptual decomposition into the potential flexibility and the rate of flexibility. The temporal ratio of each state parameter represents the rate and the utility increment to respect the state parameter evaluates a potential flexibility. Based on potential and rate flexibility, we can understand the existence of manufacturing systems including flexible technology, but showing low flexible performance. They have potential flexibility but a very low rate, resulting in rather low flexibility. This definition of flexibility allows comparing two different manufacturing systems based on the same utility function defined by the decision-maker, but containing different state parameters, which belongs to each specific system. In addition, this flexibility definition covers also its dual nature. From an operational perspective, flexibility results from little variations of utility between two states, but at a significant rate (short-term). Besides, the strategic use of flexibility results from significant variation of utility with respect to state parameters at a low rate (long-term). Partial derivatives of utility with respect to state parameters in (3) represent the additive contribution to variation of each factor *ceteris paribus*. They can be identified among the classical operational types of flexibility (Calvo *et al.* 2003).

Focused on agility, product flexibility represents the capability of introducing new products for manufacturing without affecting overall performance, directly related to the temporal dimension of changes that agility imposes. Modular product designs and final customised assembly will help to support it.

4. Complexity quantification in manufacturing systems

Some indicators of manufacturing system complexity growth can be found in the increasing number of variants of products from a basic model, the shorting time of design and production lead-time of new products, the increasing effort in information transactions, the management of materials processing or the rising rate of fixed costs (Wiendahl and Scholtissek 1994). Although, literature does not show a unique approach about its definition and measure. We have adopted a systems quantitative approach. In this sense, a complexity definition is the variety of states in the system (Beer 1970). More dynamic, McCarthy (1995) defines complexity as a system attribute that increases when the number and variety of elements and their relationships increase, at the time the level of predictability and understanding of the system as a whole decreases. Noteworthy, while complexity can create uncertainty, flexibility is a reaction against it. General features of complexity include uncertainty associated with a high number of states, irreversibility and non-linear response. These initial clues of manufacturing complexity make interesting its reduction. In order to face it, a first step is to establish the complexity concept boundaries and its measurement methods. Based on the concept of informational entropy (Shannon 1948), a set of measures has been developed and received broad attention. According to Calinescu *et al.* (2001), the approach of static complexity by Deshmukh *et al.* (1992), can be used for decision-making complexity. It is an entropy-based measurement of system states: Possible combination of operations and machines for every part. This metric can also represent the complexity of the decision tree of the production planning. Therefore, we consider that decision-making from an industrial implementation must enclose a global priority on the whole system. This requires a model including only the main influences and the objectives assessment, as well as uncertainty or risk estimation. A drawback of model simplification is a cut-off of sensitiveness of a complex emergent behaviour. Nevertheless, manufacturing complexity has been identified as scale dependent, so the simulation model can catch system complexity at the scale it represents the system behaviour.

Similarly, for structural complexity, *Hs*, it can be used the static complexity (Frizelle and Efstathiou 2002), representing the assignation part-to-machine or part-to-line in assembly schedules. Let p_{ij} be the probability of the *i* resource, out of *L* lines, being in state *j*, of K_i possible configurations, so the structural complexity is

$$H_S = -\sum_{i=1}^{L}\sum_{j=1}^{K_i} p_{ij} \cdot \log p_{ij} \quad (4)$$

Noteworthy, the assessment of states probabilities in the system does not anticipate its predictability or the transition from one state to another. For equal probability of their states, flexible systems will yield greater complexity than dedicated systems, because the number of possible states will be higher. Thus, higher levels of complexity could represent higher flexibility in a system under control.

This entropy-based measure considers two dimensions of complexity: The number of states and its probability. Nevertheless, the interdependence between variables is not taken into account directly. This should be established through the system performance. Considering a manufacturing model under the technical and operational sufficient validity by Schellenberger (1974), *Hs* calculated from the simulation output might incorporate the interdependence among variables that such a manufacturing model establishes. Thus, the structural complexity of output states could approach system complexity, as the system simulation approaches system behaviour under decision-maker control.

Probabilities are *a priori* arrangements of events based on their expectation of occurrence. From this point of view, states are events recognized from system monitoring. That is, the system works mainly in a controlled path. When the process deviates in a random way, decision-maker will try to control the deviations, actuating through the state parameters of the system in order to correct the evolution. Therefore, states probabilities can be considered conditioned by the decision-maker and his/her structure of utility.

5. Decision-making on agile and complex systems

Some conceptual and formal connections between flexibility and complexity will help to integrate both for decision-making. A systemic meeting point of flexibility and complexity is the states set that the system can reach. It was remarked before that system complexity is associated with a large number of possible states. If all of them are equally probable, entropy presents a maximum for that number of states. In the other hand, an agile manufacturing system requires choosing options among all possible different states. Flexibility is perceived high when the set of states allows decision-making towards the performance goal.

A conceptual neighbourhood of flexibility and complexity is alike. The basic utility idealisation theory and the fundamental laws of thermodynamics can be interpreted isomorphs, on a macroscopic view of the system (Smith and Foley 2002). In particular in a closed system, entropy will never decrease almost-surely, while in the utility field a decision-maker will never voluntary accept a reduction of utility. The informational connection of flexibility and complexity seems to be uncertainty. Flexibility has always been considered an operative and strategic countermeasure against uncertainty. Complexity grows along uncertainty in its entropy-based approach, since states of equal probability give little information to make a decision. In addition, flexibility and complexity are additive by the definitions adopted. Flexibility is additive, as temporal incremental ratio of utility, for mutual preferential independent contributions to the utility function, as exposed above. Similarly, entropy-based view of complexity is additive as entropy is additive by its logarithmic formulation. Therefore, a convenient complementary role of flexibility and complexity is proposed: Decision-making on agile manufacturing through the utility and complexity evaluation of the system states. State outputs and their utility based on simulation could be considered a tool of the decision-maker. Utility evolution (flexibility) comes from the aggregation of cost, quality or delivery factors, so it is close to the real system. In addition, complexity can be felt across the system. Frizelle and Efstathiou (2002) point out that the queues and bottlenecks are clear signs in relationship with complexity inside a manufacturing system.

The set of all possible state utilities can be interpreted under a statistical analogy as a probability distribution. Castagnoli and LiCalzi (1996) interpret the expected utility as a procedure to rank lotteries based on their probability to outperform an independent stochastic benchmark. Lotteries are random variables that take their values in the domain of utility distribution and they are exogenously given to the decision-maker, added to the utility structure. Among other interpretations, the stochastic benchmark is the expected probability that outperform a deterministic threshold or target. This threshold is imperfectly known (probabilistic distribution), and the state utility distribution represents the uncertainty about the right (deterministic) target to apply. These approach by Castagnoli and LiCalzi (1996), allows us to include utility and its external target in the decision-making process, instead of utility and some lotteries. In manufacturing system seems to be more intuitive the goal under uncertainty than the decision-making process based on lotteries. Under these premises, the set of possible states and their utility values can be interpreted as a probability distribution, which represents the uncertainty of reaching a deterministic target of utility, independent of the lotteries the decision-maker is facing to take a decision (expected utility based on those lotteries). At this point, flexibility gains significance as the temporal ratio of incremental utility between two states. The utility distribution of the possible states is an assessment of the uncertainty to reach or surpass a target of utility. Passing from one state to another of greater utility is an act (*versus* a lottery) of reducing the uncertainty of reaching a target of utility. Thus, a flexible change is an uncertainty countermeasure in the decision-making process.

This distribution of probability or uncertainty could represent the probability of occurrence of the states, so the complexity of the system can be estimated through its entropy-based (informational) measurement, *H*. For a continuous utility distribution (Abbas 2006)

$$V(x) = \int_{x\_min}^{x} v(y)dy;\ and\ \int_{x\_min}^{x\_max} v(y)dy = 1, by\ definition\ \ v(x) = \frac{dV(x)}{dx} \tag{5}$$

$$H(x) = -\int_{x\_min}^{x} v(y)ln(v(y))dy\quad and\quad H = -\int_{x\_min}^{x\_max} v(y)ln(v(y))dy \tag{6}$$

Where, in general, the scalar utility function by (2) is a non-decreasing function of the state variables. And *V(x), H(x)* note the increments of utility and entropy taking decision on the evolution of one of them, the variable $x \in \{x_1, x_2, \ldots, x_n\}$, that take values in the interval *x_min* and *x_max,* ranking states from less to most preferred. In addition, for a discrete set of events the same formulation can be rewrite (Abbas 2006):

$$\Delta V_j = \sum_{i=1}^{j} \Delta v_i \quad and \quad \sum_{l}^{L} \sum_{k}^{K} v_{kl} = 1 \tag{7}$$

$$H_j = -\sum_{i=1}^{j} \Delta v_i \, ln(\Delta v_i) \tag{8}$$

Let ΔV_j be the discrete utility value that correspond with the component j of the utility-increment vector. Its components, $\Delta v_{i,}$ are equal to the difference between the consecutive elements in the utility vector, which ranks in order the L x K utility prospect values (states) from null to one, for L assembly lines with K configuration of each line.

With no loss of generality, except a constant of proportionality, we formulate (8) in natural logarithms, convenient for easier integration in the case of the continuous approach. From (3), (5) and (6) or (8), we can express complexity variation as a function of utility

$$\frac{dH(x)}{dV(x)} = -ln[v(x)] \quad or \quad \frac{\Delta H_j}{\Delta V_j} = \frac{\sum_{i=1}^{j-1} \Delta v_i \, ln(\Delta v_i) - \sum_{i=1}^{j} \Delta v_i \, ln(\Delta v_i)}{\sum_{i=1}^{j} \Delta v_i} \tag{9}$$

Where $V(x)$ is the cumulative distribution function of utility of x state parameter and $v(x)$ the density function of the probability distribution $V(x)$. From (9) and (5), we could interpret the sign of variation of complexity and expected utility should be the same, so an increase of complexity supports greater flexibility under uncertainty. In other terms, in order to contain uncertainty, increments of complexity and increments of utility compensate each other. From (9), the temporal incremental ratio of complexity to flexibility could be an estimation of the uncertainty level, considering the $v(x)$ relationship with the probability of events, by (7). Obviously, situations of low complexity and high utility are preferred. Reducing initially uncertainty through contractual mechanisms could allow it. Current competitive industrial environments seem to make it difficult.

6. Systemic sustainability of manufacturing

Agile systems are open, flexible and complex. The thermodynamic principle of non-decreasing entropy for a close system is not directly applicable to the evolution of a manufacturing system. From raw materials to energy, from information to engineered products, manufacturing systems are open systems. This is an important reason to consider their sustainability. A general definition of sustainability in elementary terms can be formulated (Gallopin 1996), from V as a valuation function of the system outputs and O_t as output vector at time t, as follows:

$$V(O_{t+1}) \geq V(O_t) \qquad (10)$$

That is, for Gallopin (1996) a sustainable system is a system of non-decreasing 'worth' in time. In this sense, we have intentionally noted it like the former utility function. It represents the same concept of expected utility of the system, in a broad sense for the society. A first identification of the utility function with the worth to the society of the system can yield this first sustainability criterion. Nevertheless, this approach lacks the organisational objectives of survival or goal-setting evolution for the system.

From a systemic perspective, the principle of requisite of variety establishes that the variety in the control of the system must be equal to or larger than the variety of the perturbations in order to maintain stability (Ashby 1958). Thus, variety generation (entropy) is necessary to survive. Considering the increasing uncertainty of manufacturing systems in a global market, we could conclude that a manufacturing system under control can only evolve increasing its complexity. Note that the process of controlling a system becomes harder as its possible states increase. In fact, controlling is a process of variety destruction to maintain the system in the assigned work-point. Although, a complementary perspective can be adopted, interpreting agile systems as adaptive self-organized entities. The survival of a manufacturing system through agility can be view as the dynamic stability of a dissipative entity of asymmetric transitions (Heylighen 1992), where state of energy emission are more probable of those where energy is absorbed. Former author affirms that this hypothesis is equivalent to the law of maximum entropy production, so the system can reduce its internal complexity. In this view, systems configurations tend to become more stable emitting energy in the process, conversely to the most common interpretation of the second law for close systems, namely that disorder and homogeneity tend to increase. This is an interpretation of manufacturing systems as open, dissipative and complex structures. Its evolution can be recognised in some features of current manufacturing systems. Manufacturers seek differentiation from competitors, product variety and sales increases, instead of product homogeneity and activity reduction. This fact is compatible in an open system to the decrease of its entropy through a continuous interchange of energy and goods, obtaining stability (future or survival) as a dissipative entity. In this approach of agile manufacturing as a dissipative system, sustainability is viewed as the long-term survival of the system in its environment and it concerns the ability to generate variety interacting with its environment in a dissipative process that allows a decrease of entropy (complexity) inside the system.

Good manufacturing systems are imagined offering goods at a high quality, low cost and produced quickly under schemas of continuous variety change for customer satisfaction. Meanwhile, we aim an internal configuration based on simple processes and a big effort of commonality of parts that do not yield many possible alternatives, because many state options usually come from overdimensioned systems. Therefore, a sustainable manufacturing system interchanges its goods, energy and disposals with the market and its environment at low internal entropy. Thus, we propose to define sustainability for a manufacturing system as

$$Sustainability(t) = S(O_t) = \frac{\Delta V(O_t)}{\Delta H(O_t)} \tag{11}$$

A utility increase and/or internal complexity reduction enhance sustainability of the system itself. In addition to the constructivist modelling of flexibility and complexity from utility, a thermodynamic analogy as a dissipative system arises. The worthiness (utility of manufacturing output for the society) can be seen as the energy the system interchanges. The complexity or entropy of the system assumes the same role than the thermal entropy as a macroscopic measure of microstates. The ratio of energy transfer at a level of entropy (utility change at an internal complexity) is the macroscopic temperature at equilibrium, the sustainability in this analogy. Note that under a thermodynamic criterion, a system is more capable of developing a cyclic work when its temperature is higher. This approach connects to the exergy approach to sustainability (Wall and Gong 2001). Likewise, sustainability of a manufacturing system increases when the ratio of incremental utility *versus* incremental complexity increases.

When we compare this criterion (11) with the former decision-making ratio between utility and complexity (9), a new connection of concepts appears. The criterion of sustainability represents the reverse of the uncertainty of utility to respect the state parameter *x* at a point time, that is its certainty. Thus, sustainable systems are those that evolve in evolutions towards greater certainty, so towards higher order under-control or predictable system. In addition, in a continuous approach the temporal probability distribution of utility to respect the state parameter *x* is directly related to sustainability.

$$S(x_t) = -\frac{1}{\ln\left[v(x_t)\right]} \quad or \quad S_j = \frac{\sum_{i=1}^{j} \Delta v_i}{\sum_{i=1}^{j-1} \Delta v_i \ln(\Delta v_i) - \sum_{i=1}^{j} \Delta v_i \ln(\Delta v_i)} \tag{12}$$

Note in (12) that sustainability is evaluated at time *t*. For a continuous analysis through a state parameter, x_t . For a discrete approach, states are arranged in increasing utility through the index *j,* and the associated utility vectors are evaluated at time *t.* From (5) and (12), sustainability is positive, increasing as the probability of the utility (function of density) *v* increases.

7. A case simulation analysis

Final assembly represents the last step of postponement of final variety. A simple model of product-to-line assignation in a hybrid (semiautomatic) assembly system is used. Authors have applied this model to analyse flexibility and complexity (Domingo *et al.* 2005, Calvo *et al*. 2006). In this model, the state parameters include products definition by manufacturing standard time per part and its daily demand. Assembly lines are defined by its layout, machines, operators and processes established for the products they can process. Layout, machines or processes are established during line design. Therefore, the capability of a line to produce a product is initially determined by design. The incidence matrix between products and lines is an input that establishes that possibility. Significant line operative parameters include the number of operators and cycle time. Production is managed just-in-time and zero stock, so every day planning is to produce the day after deliveries. Different utility functions and goals can be used to maximize utility: Minimizing reduced cost (C_r), noise-to-signal ratio of parts work content in the lines (reduced quality, Q_r), makespan of the daily production (reduced delivery, T_r) or a weighted addition of them, that represents the relative importance of the different productive factors to the decision-maker. In addition to the pure individual factors, for illustration we use also $(0.2C\_r+0.3Q\_r+0.5T\_r)$. In order to evaluate the variety effect, from an initial portfolio of 30 products we reduce the variety (suppressing products from the bottom of product listing) maintaining the workload in total hours (proportional for each product to the relative volume in the original table of 30 products). Note that the reduced cost represents the hour cost per hour of standard load, so it can be seen as a unitary cost or efficiency. In the same sense, reduced delivery T_r measures makespan of the daily production rated by the average load of the assembly lines. In both cases, the relative measure maintains its reference, since the total workload is constant for different number of products (Figure 1).

(Figure 1 about here)

The maximum, v_max, and mean, v_mean, utility reached in the set of system states, as well as complexity H, both are represented for a weighted criterion of utility function, $0.2C\_r+0.3Q\_r+0.5T\_r$. At a first glance, we appreciate that v_max and v_mean approximate each other as the number of product increases. That means a dispersion reduction in the distribution of solutions, so towards system stability, that constitutes an internal variety decrease indicator. Even when the number of solution increases, complexity H can decrease when the number of products increases. Therefore, a higher number of states is possible, but under less uncertainty. Noteworthy, this criterion represents the consumption of resources that exhausts internal performance of the agile assembly lines, in a decreasing or constant evolution of flexibility. In the other hand, we can interpret that a greater variety offered to the customer for the same workload can yield an increase of product sales or a better part price. These benefits, not included in the model, could probably compensate or overpass that effort of utility reduction.

Next, we can calculate sustainability from (12), based on the statistical approach of each utility distribution. When it is followed an aggressive criterion of maximizing utility (v_max), the system looses sustainability when increasing variety. The number of states that maximize utility are ordinary infrequent. According to Heylighen (1992), under a systemic perspective, the principle of selective retention establishes that stable configurations are retained, while unstable ones are eliminated. Consequently, system evolution through states of higher likelihood, v_mean, plays in favour of sustainability. Like the principle of selective retention, this statement seems to be tautological, but it is not so evident for manufacturing system where the maximum performance at any time seems to be the path for survival. In particular, when adopting a simple definition like (10) that anticipates a maximization of utility for sustainability increase.

(Figure 2 about here)

The more probable and numerous working points at mean utility *v_mean*, Figure 2, presents greater sustainability and a positive evolution than *v_max,* for an increasing variety. This alerts about the path of a manufacturing system for sustainability. System performance (utility) can improve but the complexity of the system should be contained, in order to increase sustainability. Very complex manufacturing systems can collapse when are not properly controlled. This trade-off between complexity and performance suggest that sustainability from an equilibrium state could be closer related to system stability. The likelihood of temporal equilibrium of an open system in its environment seems to be more influent for sustainability than with the optimisation of the performance.

8. Concluding remarks

We have presented a new and general integrated framework for flexibility and complexity join measurement based on utility and its distribution. Both are related each other through the uncertainty of changes and the decision-making processes on the system. Useful for decision support systems, flexibility and complexity could become some remarkable factors for decision-making, in particular for very dynamical systems of agile manufacturing. We have revised sustainability of agile manufacturing systems considering them as dissipative open systems. The sustainability criterion proposed is based on previous decision-maker key drivers of flexibility and complexity (utility and entropy). Nowadays, the emergent behaviour of complex systems is object of intense research. This systemic approach to sustainability could be useful for systems research and it can easily incorporate engineering, business or environmental factors through the utility function. Including not only the classical approach to performance, but also the evaluation of the system internal complexity. This general approach is independent of the system and the additive property of flexibility and complexity will allow the partial or detailed quantitative analysis on subsystems. Therefore, the study of some concrete complexity and flexibility sources and sinks in the manufacturing system can help to improve it effectively. Quantification based on the utility distribution of the possible states the system can reach, function of the system state parameters, so finally close to practitioners and potential industrial application.

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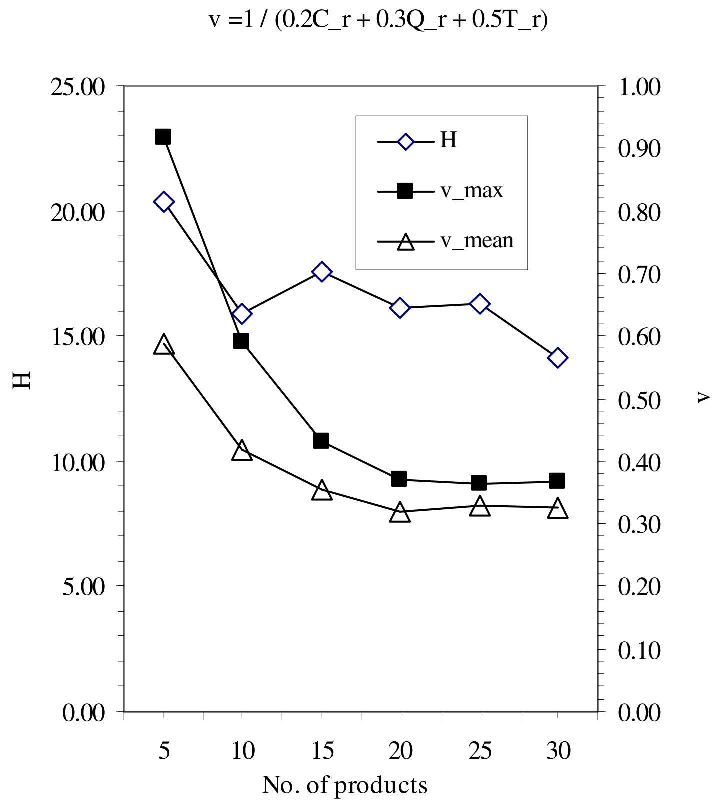

Figure 1. Utility and complexity evolution vs. variety increase

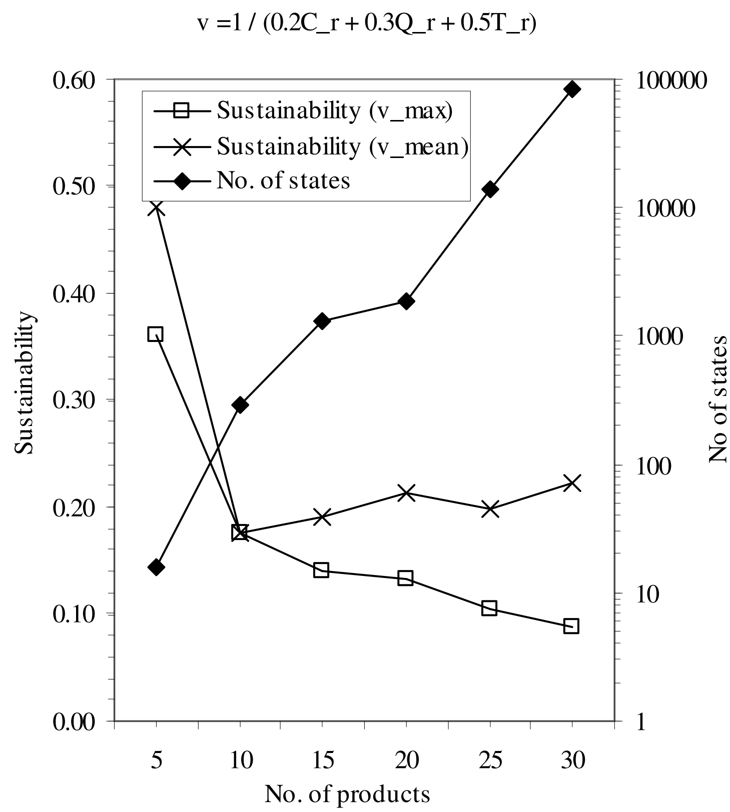

Figure 2. System sustainability evolution vs. variety increase