Managing highly flexible facilities: an essential complementary asset at risk

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Abstract

Purpose – Twenty first century problems are increasingly being addressed by multi technology solutions developed by regional entrepreneurial and intreprepreneurial innovators. However, they require an expensive new type of fabrication facility. Multiple technology production facilities (MTPF) have become the essential incubators for these innovations. This paper aims to focus on the issues.

Design/methodology/approach – The authors address the lack of managerial understanding of how to express the value and operationally manage MTPF centers through the use of investigative case study methods for multiple firms in the study.

Findings – Owing to the MTPF centers' novelty and outward similarity to high volume semiconductor fabrication (HVF) facilities, they are laden with ineffective operation and strategic management practices. Metrics are the standard for both operational and strategic management of HVF facilities, yet their application to this new type of center is proving ineffectual.

Research limitations/implications – These new types of regional economic resources may be at risk. A new approach is needed.

Practical implications – The authors develop an operational and strategic metrics management approach for MTPFs that are based on these facilities' unique nature and leverages both the HVF and R&D metrics knowledge base.

Social implications – Innovations at the interface of micro technology, nanotechnology and semiconductor micro fabrication are poised to solve many of these problems and become a basis for job creation and prosperity. If a new management technique is not developed, then these harbingers of regional economic development will be closed.

Originality/value – While there is an abundance of research on metrics for HVF, this is the first attempt to develop metrics for MTPFs.

Keywords Entrepreneurship, Metrics, Nanotechnology, Technology, Innovation, Research and development

Paper type Research paper

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1. Introduction

There is a gap in strategic entrepreneurial thought where entrepreneurial action requires crucial external complementary assets (Teece, 1988) which are important to regional economic development based on entrepreneurial action (Walsh and Linton, 2000). The authors add to the body of literature that addresses complementary assets (Hitt *et al.*, 2001; Shane, 2001). We choose small technology highly flexible facilities (see the Appendix, Table AI) as our critical complementary asset focus.

These highly flexible facilities are critically important for entrepreneurial action and economic development (Linton and Walsh, 2008). Second, these facilities are extremely costly to build and maintain (Van Heeren *et al.*, 2003; Walsh, 2004); costs which far outpace the resource base of even high technology based entrepreneurial efforts. Third, many see small technology as the harbingers and enablers of the next Schumpeterian economic wave (Walsh *et al.*, 2000), Finally, firms based on these technologies are already starting to solve problems in a uniquely valuable manner (Anson *et al.*, 2008; Corbett *et al.*, 2000; Linton and Walsh, 2008; Romig *et al.*, 2007; Thukral *et al.*, 2008).

Yet these small technology highly flexible facilities are at risk. Entrepreneurs, facility managers and policy makers using current management techniques are hard pressed to convey these facilities operational effectiveness and strategic value. Effective strategic and operational management is required to keep these knowledge assets effective (Li *et al.*, 2009).

Accomplishing this requires a general understanding of the nature of the small technology based modern production processes. Modern production processes (also called convergent technologies) are progressively more multiple root technology based and are often superseding more traditional solo or single root technology production processes (Eijkel *et al.*, 2006). The modern production process causes operational and strategic complexity.

Current best practice (Bergek and Norrman, 2008) strategic management of these facilities is using traditional single root technology high volume facilities. The results of this practice have not been encouraging and the facilities managers discussions of "doing the right thing" are not as compelling due to environmental factors. Several environmental factors are leading to an increased scrutiny of small technology based highly flexible facilities:

- Semiconductor manufacturing facilities or high volume facilities are moving from the more developed economies of North America and Europe to the emerging economies of Asia (Ernst, 2010; Globalfoundries, 2009).
- Financing for these facilities is being more harshly scrutinized during a period of economic uncertainty.
- Small technology facilities are often too costly for any one firm. Increasingly regions are seeking support from governmental bodies (Elders and Walsh, 1999).
- Small technology facilities have matured from purely research facilities to multi-use facilities with little or no operational scrutiny (Myers *et al.*, 2000; Naughton, 2005).
- The success of high volume facility metrics management has made metrics management and particular high volume tactility metrics the methodology of choice for all facilities (Benson *et al.*, 1995; Sattler *et al.*, 1997).

- Highly flexible facilities are still perceived by many founders, managers and policy makers as extensions of semiconductor based high volume facilities and they expect to see high volume facility metrics.

We initiate our investigation of these strategic assets by delving into foundational strategic literature, strategic entrepreneurship literature and strategic literature on technology entrepreneurship in particular. We review the theory that supports the current use of metrics. We choose the case study method (Eisenhardt and Graebner, 2007; Yin, 2009) to interact with one high volume facility and five highly flexible facilities to garner the rich information needed to advance the field. We find that metrics usage is meeting with resistance in highly flexible facilities and when used has limited operational success. Furthermore, some highly flexible facility managers are so frustrated with their initial use of high volume facility metrics that they simply use none at all. We find that this challenge has produced an environment where managers of highly flexible facilities are not able to effectively use even a minimum common set of metrics, which is seen as problematic. Finally we provide a model for highly flexible facilities managers and stakeholders for metric selection based on both our finding and the literature.

We fill a literature gap concerning the strategic action of essential complementary strategic assets. We provide a model that managers of highly flexible facilities can use to express both their facilities strategic value and as a selection criteria for metrics management-based operations.

2. Literature review

The highly flexible facility is important to a variety of stakeholders. To a small technology based entrepreneur it is an essential strategic resource that is most often financially out of reach (Walsh, 2004). To a regional or national policy maker a highly flexible factory is a complementary asset for national policy or regional development (Romig *et al.*, 2007). Here we provide value to the academic and practitioner community by linking the development, sustainability and operations management of this asset to strategic entrepreneurship literature, strategic technology entrepreneurship literature and general strategy literature to further the fields understanding of this issue.

Entrepreneurs derive sustainable competitive advantage from exploiting market gaps (Kirzner, 1997), lower transaction costs (Williamson, 1985) or taking advantage of technological advances (Spencer *et al.*, 2008). Strategic entrepreneurship has many and often competing strategic perspectives (Hitt *et al.*, 2011). While researchers in these fields demonstrate different perspectives of thought on just how to create sustainable competitive advantage, most of them highlight the importance of innovation (Ireland and Webb, 2007). Complementary assets like highly flexible facilities find strategic value for firm renewal, sustained regeneration, domain redefinition, organizational rejuvenation and business model reconstruction (Covin and Miles, 1999). We integrate strategic entrepreneurship to general strategy by focusing on the internal and external environment of the venture from a technological point of view (Kuratko and Audretsch, 2009).

We choose the objective rather than the normative approach to strategy, since the normative approach of prescribing metrics that worked in one arena to another is a fundamental source of contention of managers of highly flexible facilities (Mintzberg, 1994). We have taken an "inside out" strategic perspective and chosen the competency (Prahalad and Hamel, 1990) over the Resource Based (Barney and Wright, 2001) perspectives due to its relatively larger emphasis on technology (Katzy and Crowston, 2008; Nath *et al.*, 2010; Terziovski, 2010). The competency perspective highlights technology, production skills, and their associated management practices as the core of competitive advantage. Furthermore, the resource based strategic perspective has been found lacking when considering either new competition or industry drivers that offer competitive advantage in dynamic markets (Saarenketo *et al.*, 2009). As highly flexible facilities are essentially technology-based, the competence perspective (Walsh and Linton, 2011) with its focus on technology and its management is a superior fit for our research.

Technology and its management is of critical importance to a competence perspective of strategy. To remain competitive, most firms must continually acquire and/or develop new skills (Linton and Walsh, 2004). Highly flexible facilities are the source of these manufacturing and technology development-based complementary assets in small technology. To date the much of the strategic entrepreneurship literature on innovation has focused on an organization's characteristics (Damanpour, 1996). We seek to expand this through the competency perspective. We operationalize the competency based perspective though the industry standard metrics approach.

Metrics can condition data into useful and compact information that is easily assimilated (Pich *et al.*, 2002). Further, researchers have suggested that the selection of metrics must be tied to the strategic imperatives of a firm of facility to attain maximum utility (Drongelen-K. and Bilderbeek, 1999). Foundational metrics management suggest that metrics must be tied to the product and process metrics mix of a facility (Cordero *et al.*, 2005; Hayes and Wheelwright, 1979).

Metrics management is the standard for the highly successful management of high volume semiconductor facilities. Due to the outward similarity between these facilities and highly flexible small technology facilities they have been directly applied. The same set of metrics are unlikely to be applicable to both extremes (Hayes and Wheelwright, 1979).

Research on semiconductor based high volume facilities show that "wafer starts" or the amount of material initiated into a process and the associated total system process yield are the most important facilities management metrics (Sattler and Schlueter, 1998). Metrics management has pushed these high volume facilities towards automation wherever possible (Goldratt and Cox, 2004). Yet as change and innovation become important the "lot move" metric or the movement of one batch process quantity to the next process step becomes the more important management metric (Goodall *et al.*, 2002). Highly flexible facilities introduce change on many more dimensions and emphasize skilled labor knowledge (Comerford, 1993). The fundamental differences between these two types of facilities provides us with a starting point for the development of an effective management model for highly flexible facilities.

2.1 Highly flexible facilities

The term Multi-technology High Mix Low Volume facility (MTHMLV) was introduced to define high volume semiconductor flexible facilities (Myers *et al.*, 2000; Naughton, 2005). The authors have further simplified this acronym through the addition of small technology to create the term highly flexible facility. Both our effort and the earlier work show that the workflow varies greatly between highly flexible facilities and high volume facilities and further states that operational or strategic metrics must mimic the needs of the facility.

The highly flexible facility now includes the new tasks of research and development, product and process maturation, innovation, and design validation (Pich *et al.*, 2002). It is based on not simply semiconductor processing technology but nanotechnologies and micro electro mechanical systems as well. High volume facilities and highly flexible facilities differ greatly in operation and strategic value.

2.2 High volume facilities metrics

Metrics management in semiconductor high volume facilities management became recognized as semiconductor surface process technologies became the dominate manufacturing semiconductor process in the late 1950s (Kilby, 2001). Today, most semiconductor products are silicon based, produced by a semiconductor surface modification process and fall into well-defined product areas (ITRS, 2008). The semiconductor industry produces well over $261.2 billion in commercial devices annually, and its devices are found in products affecting nearly every aspect of our daily life (SIA, 2008). Despite this success, the number of semiconductor micro fabrication facilities worldwide is shrinking.

Here we limit the our metrics investigation to the high volume facilities materials to device manufacturing even though those of packaging a device (often called back end) are important. We build on semiconductor metrics classification schemes (Sattler and Schlueter, 1998). We do so by separating these metrics into those focused on an entire process which we name "global" metrics and those focused on a single process steps which we name "local" metrics (Limanond *et al.*, 1998).

2.2.1 High volume facility global metrics. Many global high volume facility metrics focus on productivity and yield (Goldratt and Cox, 2004). We provide a selected list of high volume facility based global metrics in Table I as foundations of thought. First, we will discuss the utility of high volume facilities yield and wafer start metrics for

Author	Characteristic	Analytical technique
Maynard *et al.* (2003)	Yield	Project costs
Sattler *et al.* (1997)	Yield/wafer starts vs cap	Ranking
Benson *et al.* (1995)	Wafer starts capacity	Factory performance
Leachman and Hodges (1996)	Product mix	Benchmarking
Sattler and Schlueter (1998)	WIP/wafer starts WIP WIP	Case study
Fallon *et al.* (1995)		Case study
Bonal *et al.* (1996)		Equipment efficiency
Ishii and Watanabe (2002)	Control: Information	Case study
Wu (2002)	Control: 300/450 comparison	Case study
Goodall *et al.* (2002)	Control: fab tool cluster setup	Manufacturing cost
Jacobs *et al.* (2001)	Cycle time management	Case study
Dietrich *et al.* (2004)	Cycle time management	Case study
Montoya-Torres (2006)	Cycle time management	Case study
Wagner (2001)	Failure analysis	Case analysis
Guidi *et al.* (1999)	Simulation and automation	Modeling
Mozumder and Loewenstein (1992)	Simulation and automation	Modeling

Table I.
High volume facility global metrics

highly flexible facility management. Next, we will address the utility of Cycle Time (CT) or the time it takes to complete an entire process and Work in Process (WIP) measures (Montoya-Torres, 2006). Finally, we discuss high volume facility management practices centered on information sharing, simulation automation, clustering and facilities upgrade in the following.

High volume metrics such as entire process yield and the amount of material that initiate the process or "wafer starts" which was developed through benchmarking techniques (Benson *et al.*, 1995) and are key performance measures. This was further linked to the facility as it approached capacity (Leachman and Hodges, 1996). These metrics become important for highly flexible facilities by adding product mix and the required number of process steps (Sattler *et al.*, 1997). For these types of measures to be useful in highly flexibly facilities, the product mix as well as facility activity mix would have to be much more emphasized. Finally production process speed (cycle time) measures are essential to high volume facility operation management (Montoya-Torres, 2006) and many of these focus on traditional bottleneck processes (Bonal *et al.*, 1996; Fallon *et al.*, 1995; Sattler and Schlueter, 1998).

A global metric centered on process speed is found in the process step named lithography (Jacobs *et al.*, 2001). Process step limitations to throughput is not overcome by simple process station redundancy but rather by understanding the scope of each processes or task required (Dietrich, 2004; Maynard *et al.*, 2003) especially in highly flexible facilities. Yet most process time metrics other than lot moves have limited theoretical backing.

We next discuss metrics derived from computer-aided efforts. Many of these applications hold promise for highly flexible facilities due to the nature of parameters. For example, modeling is used to define bottlenecks for high volume facilities and modifications to this process can make it applicable to highly flexible facilities (Guidi *et al.*, 1999). Further Mozumder and Loewenstein (1992) discussed the focus change in a re-facilitation. He described transitioning from one size of materials input material to another (Wu, 2002). This is especially important for highly flexible facilities since many centers are older semiconductor facilities, which have been refocused.

Computer aided metrics efforts focused on process step manufacturing tool clustering and re-clustering metrics (Goodall *et al.*, 2002) have great potential application in highly flexible facilities do to their need for process scope. Further, computer aided decision tool metrics for high volume facilities failure analysis (Wagner, 2001) have potential for highly flexible facilities. Finally, the exploration of limiting information flow to workers in high volume facilities (Ishii and Watanabe, 2002) is simply not useful for the knowledge worker required in highly flexible facilities.

2.2.2 High volume facility local metrics. The complexity in highly flexible facilities are defined by the distinct natures of their three main technology and the scope of very different tasks. High volume facilities complexity is defined by products produced by a large number of repetitive tasks. High volume facilities performance originate at the process step level. Semiconductor based high volume processes routinely achieve overall yields of over 90 percent meaning the process steps must yield nearly perfectly (Appleyard and Brown, 2001). We provide a selected group of four types of local metrics that are either potentially important to high volume facilities in Table II.

Author	Characteristic	Analytical technique
Appleyard and Brown (2001)	Labor usage	Case study
Croft *et al.* (2001)	Labor	Case study
Meyersdorf and Yang (1997)	Tool usage	Temporal
Konopka and Trybula (1998)	Tool usage	Temporal
Foster and Nugent (2000)	Tool usage/WIP	Temporal
Mozumder *et al.* (1994)	Wafer uniformity	Yield
Smith *et al.* (1999)	Wafer uniformity	Yield
Herrmann *et al.* (2000)	Simulation and automation	Modeling
Hallas *et al.* (1996)	Tools	Cost
Miller (2004)	Tool utility	Cost
Limanond *et al.* (1998)	Tool utility	Cost
Kim and Lee (2003)	Tool utility	Cost

Table II. High volume facility local metrics

Even though less than 10 percent of the production cost of any high volume facility are labor costs, the cost is of concern (Appleyard and Brown, 2001). This has driven high volume facilities to embrace automation at some level (Croft *et al.*, 2001). These authors discuss theoretical labor intensive versus automated facility crossover point but the nature of highly flexible facility is that is knowledge intensive and not a very attractive managerial tool for highly flexible facilities.

Another set of local metrics is temporal in nature and refers to the number of process steps that can be done in a given period of time (Herrmann *et al.*, 2000). A better temporal metric for highly flexible facilities is how long it takes a specific tool to be reset for differing layer thicknesses and exposure times and from that to process step contribution to overall process flow time (Meyersdorf and Yang, 1997) and its link to facility profitability (Foster and Nugent, 2000).

The third group of local metrics is process step yield uniformity. Incoming material at each process step in both the highly flexible small tech facilities and semiconductor high volume facilities can yield differently due to the position of the material when it is processed. The capital equipment chosen to be used in high volume facilities are those that show the least position variability (Mozumder *et al.*, 1994; Smith *et al.*, 1999). Similarly high volume facilities select process step facilitating capital equipment based on reinvestment (Miller, 2004), process step capital equipment lifetime measures, specificity of the process step capital equipment (Kim and Lee, 2003; Limanond *et al.*, 1998) and process step capital equipment contribution to maintenance (Hallas *et al.*, 1996). Highly flexible facility managers choose process step capital equipment for their process scope rather it exceptional process step throughput at one particular process setting making these measure not easily transferable to their needs.

2.3 Innovation and research and development metrics

Highly flexible facilities act as engines of innovation and entrepreneurial action (Kautt *et al.*, 2007). They provide entrepreneurs and intrapreneurs with new product and process creation capabilities, the ability to perform proof of concept evaluation and the ability to provide experimentation at the interface of converging technologies (Walsh *et al.*, 1996). These tasks diverge greatly from the traditional high volume facility since they simply do not perform these functions. They are much more in line with the strategic and tactical roles found in R&D and commercial development departments of a firm (Michelin and Berg, 1985). Here the authors investigate R&D and innovation based metrics to ascertain their value for inclusion in the highly flexible facility management metrics package.

We provide in Table III a review of potentially relevant metrics from the innovation, entrepreneurship and R&D literature. We categorize them as decision-making, product and applications, or process focused. We start by recognizing that innovation management has utilized decision making metrics for many years (Abby and Dickson, 1983; Harms *et al.*, 2010; Matzler *et al.*, 2008).

Highly flexible facilities need to convey their value by demonstrating their innovation volume and decision making (Adams *et al.*, 2003) and R&D facility activities (Meyers *et al.*, 1997). The focus of a R&D based innovation center is to transfer knowledge, re-invent the corporation, provide new technology product platforms and make existing technology product lines better, faster, and cheaper (Walsh *et al.*, 1996). The idea of parallel metrics centered on R&D and marketing (Chen *et al.*, 2007) is an essential set of metrics for managers of highly flexible facilities to convey their strategic value.

Another important metric set that provides information to stakeholder concerning the strategic value of the facility are innovation metrics (Schumann *et al.*, 1995; Szakonyi, 1994) and those used to convey firm performance (Baglieri *et al.*, 2001) and system design (Chen and Han, 2006; Mihm *et al.*, 2003). The link between innovation and R&D funding and increased market dominance has been shown (Ofek and Sarvary, 2003). Yet each highly flexible facility will have differing goals. Multiple objective and subjective methods for applied metrics in innovation, product development and R&D situations (Werner and Souder, 1994). Metrics sets for facilities focused on research, development or engineering (Hauser and Zettelmeyer, 1997) are important for highly flexible facilities.

3. Methodology

We employ a case analysis methodology to generate an understanding of the differing imperatives, nature and metric utilization between small technology based

Author	Characteristic	Analytical technique
Pitch *et al.* (2002)	Choosing metrics	Operational
Kerssen-van Drongelen and Bilderbeek (1999)	Decision making	Operational
Abby and Dickson (1983)	Metric application	Operational
Adams *et al.* (2003)	Metric application	Operational
Meyers *et al.* (1997)	R&D	Core competence
Chen *et al.* (2007)	Parallel R&D projects	Strategic
Szakonyi (1994)	Metrics evaluation	Process evaluation
Schumann *et al.* (1995)	Metrics evaluation	Process evaluation
Werner and Sounder (1994)	Combining metrics	Case study
Hauser and Zettelmeyer (1997)	R&D/engineering metrics	Core competence
	R&D investment	
Ofek and Sarvary (2003)		Case analysis
Baglieri *et al.* (2001)	R&D performance	Stakeholder value creation
Mihm *et al.* (2003)	System design	Manufacturing
Chen and Han (2006)	Data envelopment analysis	throughout R&D performance

Table III.
Innovation and R&D metrics

highly flexible facilities and semiconductor high volume facilities. We limited facility selectivity bias by selecting highly flexible facilities identified in other studies (Kautt *et al.*, 2007) with differing objectives. We choose a top ten semiconductor based high volume facility to partake in the study. We had five responses in the affirmative and we interviewed more than one manager at each facility. They list of professionals included a facility manager, director, or vice president. Finally we reviewed all secondary data sources and facilities information to triangulate the data.

We utilize the case method to investigate not only differences between high volume facilities and highly flexible facilities but also the differences among highly flexible facilities. We have utilized Yin's (2009) and Eisenhardt and Graebner's (2007) case study techniques to interview firms, obtain secondary information and analyze these facilities through in depth interview observations and secondary data. We provide a summary of the findings in Table IV. We further our case study by administering a structured survey to all five firms (Fowler, 2002). The survey probes each firm's metric utilization, and we provide the results in Table IV.

	MTPF 1	MTPF 2	MTPF 3	MTPF 4	HVF
Group 1					
Nanotechnology	Yes	Yes	Yes	Yes	No
Semiconductor	Yes	Yes	Yes	Yes	Yes
Microsystems	Yes	Yes	Yes	Yes	No
Group 2					
Number of products	>100	50-100	20-70	50	2
Research vs production lots (%)	Unknown	30-70	50	40-60	0
Innovation mission	High	High	High	High	Low
Research mission	Yes	Yes	Yes	Yes	No
Processes	Yes	Yes	Yes	Yes	Yes
Project completion	Yes	Yes	Yes	Yes	No
Group 3					
No. of starts/yr.	$<10,000$	$<1,000$	$<2,000$	$<5,000$	$>50,000$
Capacity use	Low	Low	Low	Low	High
Group 4					
Tool availability	Yes	Yes	Yes	Yes	No
Engineering holds	Yes	Yes	Yes	Yes	No
Metrics	Yes	Yes	Yes	Yes	Yes
Global metrics	0 to 2	0 to 2	1	2	5 +
Local metrics	5	16	5	3	16 +
Lots moves	Yes	Yes	Yes	Yes	No
Changes in tool setup	High	High	High	High	Low
Tool redundancy	Low	Low	Low	Low	Yes
Tool scope	High	High	High	High	Low
Automation	Low	Low	Low	Low	High

Note: In this table, MTPF is used instead of highly flexible facility and HVF is used instead of high volume facility for readability

Table IV.
Case study results

3.1 Characteristics of highly flexible facilities

Our case study analysis focused on 21 characteristics of highly flexible facilities. These characteristics range from basic technologies to more specific subjects such as the degree of automation in the facility. We derived these characteristics by attending conferences focusing on small tech, reviewing a series of small technology industry roadmaps and reviewing a number of articles (Eijkel *et al.*, 2006; Walsh, 2004). All highly flexible facilities in this study are small technology based and two were in the USA and two were from different countries in Europe. The semiconductor high volume based facility was in the USA. We segmented these characteristics into four groups.

The first group is the number and nature of technologies in use in a particular facility. The second group deals with the number and difference in products offered. This measure includes the number of products, processes developed, innovation efforts embraced and research efforts undertaken at a specific facility. The third group of characteristics was designed to understand facility utilization and includes measures such as number of incoming material or wafer starts and determines both facility and capital tool process step capacity and utilization. Finally, the fourth group includes measures such as metric usage, capital tool process specific availability, number of operations decisions which require lot movement holds, number changes in process steps which require capital equipment setup changes, process step capital equipment scope and amount of automation in a particular facility.

We initiate the discussion with group I characteristics. Here we focus on three small technology platforms of semiconductor microfabrication, MEMS and nanotechnology. A facility is said to have a semiconductor micro fabrication capability if it has a bipolar or CMOS front-end process. A facility having MEMS capability has a full front-end process for one of the three types of MEMS process basis (sacrificial surface, bulk silicon micro-machining or high aspect ratio MEMS, Walsh, 2004). A facility is said to have a nanotechnology process if they have a bottom up or top down nanotechnology capability. This allows us to illustrate the differences between highly flexible facilities. The results of our investigation are found in the first three rows of Table IV.

We follow with a review of our group II characteristics. We investigated facility operations as manifested by a number of different characteristics: They are: products produced at a single facility; the amount of research versus product production lot starts; the number of processes run; the number projects completed; the inclusion of an innovation mission; and the inclusion of a research mission at a given facility. We also depict each firm's group three characteristics and place them in rows ten and eleven. These rows categorize each facility's wafer starts and tool capacity. The final nine rows of Table IV refer to our group 4 firm characteristics and are much more facility specific.

3.2 The results of characteristics review

These results are found in rows four through nine in Table IV. There are major differences between the five facilities we reviewed. When looking at group one characteristics, for example, all of the highly flexible facilities have three major technology platforms whereas the high facility has one technology platform. When examining group 2 characteristics the difference between highly flexible and high volume facilities are stark. The number of products produced by these facilities range from hundreds to 50. Further, there exists a slight but noted difference in relative use of the facility for production versus research.

We found differences between high volume facilities and highly flexible facilities when we viewed group III characteristics responses from the five facilities. Further, there are significant differences among the highly flexible facilities as well. The nature of highly flexible facilities demands flexibility in selecting and designing metrics. Highly flexible facilities have from 10,000 to considerably less than 1,000 wafer starts per year. Finally when analyzing group 4 facilities characteristics we see an extreme difference between high volume and highly flexible facilities. There are also significant differences between the highly flexible facilities.

Highly flexible small technology based facilities are characterized by three separate root technologies and their convergence increase production line complexity and generates significant tool compatibility and flexibility issues. This creates a work environment where process step capital tool scope rather than its efficiency becomes the dominant concern. Further, all high volume facilities use some form of metrics, including many that are tool based or local metrics. A recurring theme in all the highly flexible facilities was the view that a global wafer starts metrics, so important for high volume facilities, provided them no or little value. Finally, lot moves, usually not seen as exceptionally important for high volume facilities, were seen as providing exceptional value to the operation of highly flexible facilities.

The highly flexible facilities are focused on just that – flexibility –, rather than standard product manufacturing efficiency found in their high volume facilities. Highly flexible individual processing steps are just as critical as those in high volume facilities but integration measures take on new dimensions. For example, MEMS process times are often longer due to their use of silicon and other materials in both a structural and electrical manner rather than just electrical as in high volume facilities. Finally, the very nature of structural material changes in a bottom up nanotechnology provide process complexity issues never encountered in a high volume facility.

Our case study analysis demonstrates that the very nature of high volume facilities are exceptionally different from high volume facilities. Competency based strategic management and metrics theory tells us that the strategic management practice of technological varied firms should be different and that the simple transference of metrics would prove ineffective. More interestingly we found a great diversity of mission, scope and process activities within highly flexible facilities, a characteristic we did not expect to find. We decided to further our understanding of highly flexible facilities through a directed questionnaire. We developed the questionnaire using a rigorous questionnaire protocol to more deeply understand their utilization of metrics (Fowler, 2002).

3.3 Questionnaire development

We developed a metrics based questionnaire with 16 queries based on our research on metrics, the definition of a high volume semiconductor facility and the definition of a small technology based highly flexible facility and the nature of the highly flexible facility which we developed in our literature review. All five facilities in our study responded. All of the respondents and their firms remain anonymous due to the sensitivity of their work assignments. We provide our survey results in our results section which follows.

The first question served as a general introductory inquiry into the subject of metrics in highly flexible facilities as well as the high volume facility. The second question was developed to investigate the origin of highly flexible facility metrics. Specifically the degree to which these managers see them as highly borrowed from the high volume facilities. The third question inquired into the percentage of high volume facility metrics that had relevance to their particular situation. Question four focuses on actual metric use and their effectiveness for the efficient operation of their facilities.

The next set of questions was designed to introduce the concepts of global and local metrics. We asked the respondents through question five if the facilities used both global and local metrics as we defined them and question number six asked if high volume facility metrics emphasized wafer moves. Question seven queried the facility use of lot moves or how many times a unique start material set or "lot" is moved in a given facility. Question eight asked if high volume facilities metrics focused on a single process and question nine dealt with high volume metric use and technology experimentation.

Questions ten and eleven were used to ascertain information about highly flexibility facilities strategic intent and the need for new metrics around these concepts for them. The next question (question 12) was a departure from the previous style of inquiry. Each individual was asked to pick from a list or provide examples of metrics they used that are non-traditional and used in their facility.

Question 13 asked the respondents if their global metrics were of use and question 14 asked them to express the number of global metrics they used. Similarly question 15 simply asked the respondents' if they used local metrics were of use and questions 16 asked them to express the number of local metrics they used. We provided our respondents with our definitions of global and local metrics.

3.4 Results

The results are found in Table IV. Four out of the five entities responded to the first question strongly agreed that the use of metrics is an enormous benefit to the management of the facility. The lone stand out was neutral in the subject area and came from a highly flexible facility. All respondents to the second question stated that they agreed that the metrics for highly flexible small technology based facilities were derived from semiconductor high volume facilities. The response to question three of if these high volume facilities metrics applicability varied. Two highly flexible facility respondents stated that the percentage of high volume facility metrics that were useful ranged from 0 to 25 percent. The other two highly flexible facility respondents answered with 26 to 50 percent and 51 to 75 percent respectively. The fourth question focused on metric value.

Three of the highly flexible facility respondents stated that they strongly believed little value was gained from their use, one highly flexibility manager responded with a statement that any metrics were better than no metrics at all and the high volume facility manager was quite pleased with their use. The facilities managers responded to question five and six concerning the use of both global and local metrics and high volume use of wafer moves in exactly the same manner. Four individuals strongly agreed with the statement, with one individual disagreeing. All respondents to question seven, the utility of lot moves agreed or strongly agreed that lot moves were viewed as a better performing metric than wafer moves in highly flexible facilities.

All five respondents either agreed or strongly agreed that high volume metrics being focused on a single process (question 8) and further that they stifled innovation (question 9).

All respondents to question 10 agreed strongly that the strategic intent of highly flexible facilities is vastly different from that of a high volume facility. Similarly the mangers response to question 11 or the need for new operational and strategic metrics was strong with three out of the four agreed strongly and the fourth individual agreeing. The nontraditional metrics usage question provided a variety of responses. The first highly flexible facility manager reported that lot moves and the number of multi-technology based products were how their center measured performance. This was echoed by another respondent who also mentioned lot moves, but added that process steps metrics were also important. The third respondent sought percent of facility capacity usage as a metric. The fourth respondent answered that patents and the number of research papers produced was a principal metric for the organization. The high volume facilities manager response was that wafer starts and yield are the most important metrics.

The respondents answers to question 13 and 15 were that they all indicated that global and local metrics were important if not as a management tool then as a reporting tool. Similarly the answers to questions 14 and 16 were identical. The high volume facility manager responded that they used metrics in almost all of their management practice but less than ten key ones for both global and local metrics. Three of the four highly flexible facilities managers responded that 0 to two global metrics were used and 0 to two local metrics were used. Only one highly flexible facility used three to five global and local metrics.

Very few global or integrated process metrics are being used by those interviewed with the exception of the high volume facility, yet they all state a necessity for one that is accurate. Most suggested that highly flexible facility metrics should focus on lot moves. All five stated once more that they employ local or tool based metrics. Two of the fabrication facilities stated they utilized local metrics. One of the individuals interviewed listed the number of papers that are published and the patents that are applied for as their global metric. This is in direct contrast to the last question of whether or not global metrics would benefit the highly flexible facilities and their stakeholders.

We have shown that these types of facilities are different by nature and require different metrics to operate efficiently. Further, we have shown that a great variety of metrics exists that can be applied to highly flexible facilities. Next we have synthesized a metrics model for highly flexible facilities.

4. A metrics selection model for highly flexible facilities

Our literature review and case study finding suggests a metrics model that allow for selectivity from a general set of metrics that could meet the diverse needs of a small technology based highly flexible facility. We provide groupings of specific metrics designed to directly support the managerial requirements generated by the missions and capabilities of small tech highly flexible facilities in our selection model. The model is designed to assist these facilities to accurately assess, operationally utilize and present their strategic effectiveness. Our model is founded on the separation of manufacturing facilities into distinct categories. The model is selective in nature to mimic the differing missions and technologies employed by each highly flexible facility (Hayes and Wheelwright, 1979). We have provided a three factor approach based on mission focus, capability (competence) scope, and capacity (see Figure 1).

We operationalized mission by the facilities inherent nature (Hayes and Wheelwright, 1979). The mission metric selection at the top of the model. We

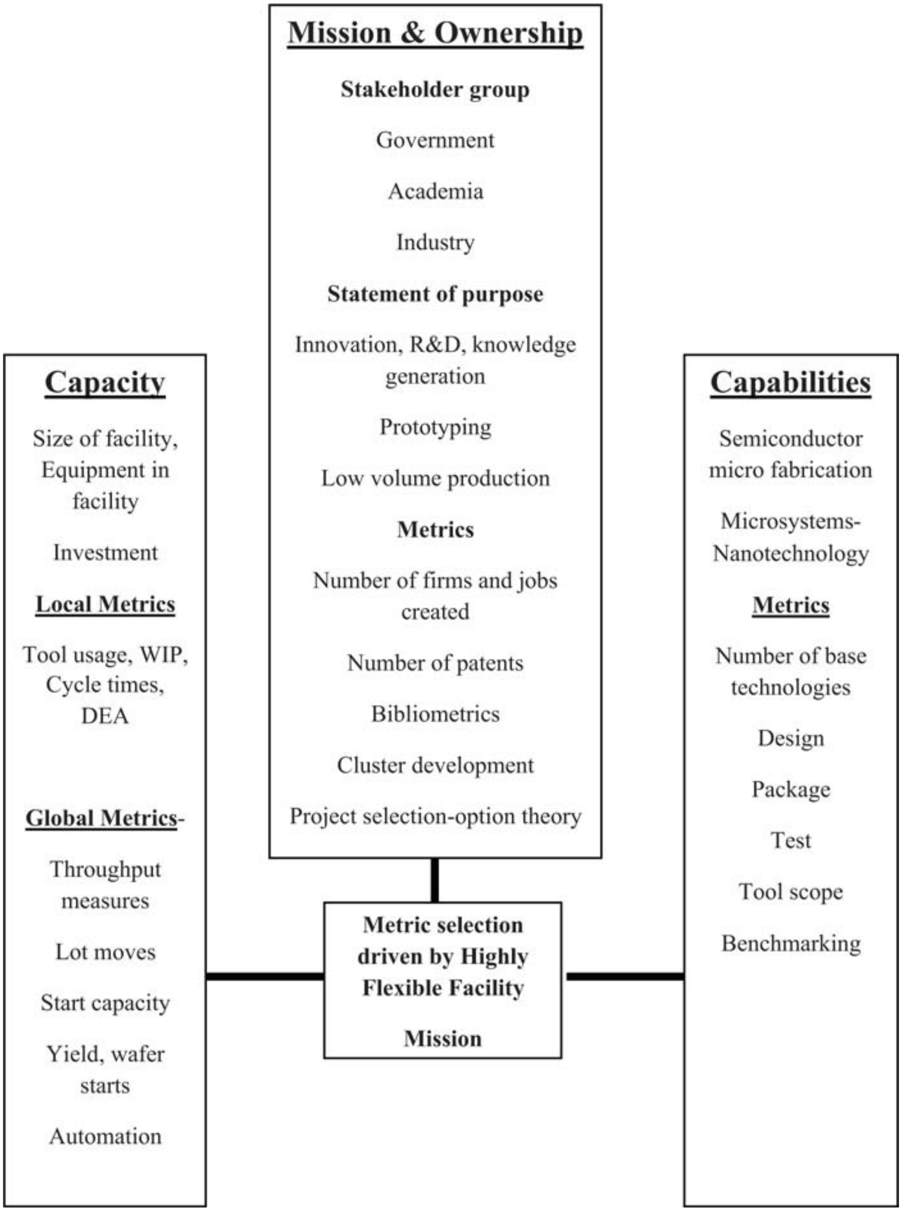

Figure 1.
Highly flexible facilities metrics choice model

develop a set of metrics that can assist managers to demonstrate strategic value of the facility through a variety of innovation and R&D metrics that speak to both facility mission and stakeholder values.

The tasks of the highly flexible facility often include: increased innovation, knowledge generation, R&D, prototyping, and low volume production. We individually operationalize these factors. We use bibliometric measures as the metric for R&D, knowledge generation and innovation. The bibliometric metrics are innovation awards, journal articles, citation rates and licenses. Further some highly flexible facilities are tasked with low volume product production which is usually tied to a specific stakeholder group. Here we utilize capacity measures. Finally, most ownership is focused on regional development, job and wealth creation. Here metrics are for example number of employees, firm attraction and spinouts. We next turn our attention to capacity.

We operationalize capacity through a portfolio capacity and complexity approach. Wafer starts are important for these facilities and bounded by complexity. The portfolio would be different for each highly flexible facility and include activities such as parts produced, processes developed, inventions and papers developed. Local capacity metrics are based on modified high volume facility metrics. These metrics must include tool change set up time included in tool usage, as well as process flow metrics such as work in process. For the global metric capacity segment some facilities might use wafer starts but lot movers is the most important element.

The final aspect to model is capabilities and highly flexible facilities operate the three small technologies root technologies such as semiconductor fabrication, MEMS and nanotechnology. Each of these base technologies is similar, but unique in their approach to metrics. Here we considered the metrics for design, packaging and testing as can be seen from Figure 1.

5. Discussion and conclusions

Building on the current literature, we examined the differences in metrics for these outwardly similarly but vastly different complementary asset based facilities. Most of the metrics in place now at highly flexible facilities are based on those historically used by high volume facilities. While these metrics work well under the automated processes that are universally used in semiconductor based high volume facilities, they do not fit the essential needs for small tech based highly flexible facilities. Given the information that was gained from the questionnaire, highly flexible facility managers prefer to use lot moves as the primary metric in their facilities. Further, there is no misuse of high volume facility metrics in highly flexible facilities they simply do not fit the needs of highly flexible facilities.

We have shown the metrics derived from high volume semiconductor based facilities retard the effectiveness of these facilities. The use of these metrics are actually putting these facilities at greater risk of being eliminated in today's climate. We have shown how metrics literature can be used to operationalize strategic entrepreneurial action. We have also provided a basis for a metrics selection model for small technologies based highly flexible facilities.

This work provides the basis for the development of new metrics based on innovation and R&D metrics to depict highly flexible facilities strategic value to stakeholders. Moreover this work suggest the modification of some global and local high facility metrics for capacity, mission and capability measures, and sets a direction for new metric development.

All respondents mentioned that the current set of metrics in use today actual hampers the innovation portion of many highly flexible facilities mandate. Their use inhibits the core mission of highly flexible facilities. Finally, that direct implementation of high volume facility metrics do little to assist highly flexible facility management in reaching either their strategic or operational goals and foster poor operations management.

The authors seek to assist in the effective management of highly flexible small technology based facilities. They are an essential complimentary asset for both regional economic development and entrepreneurial action. They are the potential harbingers and underpinnings of the next generation Kondratieff wave and due to current management measures and the economic climate they are at risk. This article is the harbinger for future investigation into the area of metrics for critical complementary assets necessary for entrepreneurship and regional development. Our limitations are associated with the limitations of a case study approach. The next step would be an empirical test of our model.

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Appendix

Readability term used	Industry term and definition for this paper	Common acronym in use or in literature
Facility	Refers to a production facility	Foundry.
Small technology	A grouping term referring to nanotechnology, semiconductor microfabrication, microsystems or micro electro mechanical systems	Microfabrication, Nano, MEMS
Highly flexible facilities	A grouping term that refers in this paper to facilities that perform semiconductor fabrication, nanotechnology, and micro electro mechanical systems. These facilities are characterized by low volume production as well as research, product and process development.	The two acronyms in use for these foundries are: MTPF (Multi-technology Production facilities) MTLVHM (Multi-technology, Low Volume, High Mix facilities or foundries)
High Volume facilities	This designation is for high volume foundries with single technology single Product focus	The two acronyms that are in common use are: HVF (High Volume facility) HVSF (High Volume Semiconductor foundry or facility)
Cycle time	The time it takes a product to go through a complete process	CT
Work in process	Work in process is the status of any product as it progresses through a process	WIP
Complementary metal-oxide-semiconductor (CMOS)	The dominant classification of surface semiconductor processing. In this group of processes are HMOS, DMOS and others	CMOS
Bipolar	One of two dominate classifications of surface semiconductor process. It has been increasingly supplanted by CMOS	Bipolar

Note: This paper has both academic and practitioner utility. We have utilized terms design for reader retention and flow. However some policy makers, industry strategist and some academics will be more familiar with these more precise terms

Table AI.
Definitions and acronyms

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Robert Tierney is currently pursuing a PhD in entrepreneurship at the University of Twente. He received a Bachelor of Science in molecular biology in 2000 at the University of New Mexico with minors in chemistry and psychology. He later earned a MBA at the University of New Mexico in the management of technology with additional work in finance and marketing. He has owned several successful businesses and currently is involved in the research of nanotechnology and MEMS.

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