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Stefan Tönissen

Economic Efficiency of Manufacturing Technology Integration

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Economic Efficiency of Manufacturing Technology Integration

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Vorwort

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Symbols and Abbreviations

Symbol	**Unit**	**Meaning**
C	€	Cost
C_{con}	€	Consumption cost of manufacturing system
C_{conv}	€	Cost of conventional manufacturing system
C_f	€	Fix cost of manufacturing system
C_{flex}	€	Cost of flexible manufacturing system
C_{oper}	€	Operator cost of manufacturing system
C_{over}	€	Overhead cost of manufacturing system
C_{pot}	€	Cost of potential factors
C_{sys}	€	Cost of machine tools within manufacturing system
C_v	€	Variable cost of manufacturing system
$C_{v,i}$	€	Variable indirect cost of manufacturing system
D	€	Contribution margin
D_{conv}	€	Contribution margin of conventional manufacturing system
D_{flex}	€	Contribution margin of flexible manufacturing system
$L_{para,l}$	qty.	Number of paralleled machine tools at l-th stage of transformation process
$L_{serial,SMS}$	qty.	Number of serial machine tools within segregated manufacturing system
K	€	Manufacturing cost per workpiece
K_{AW}	€	Order repetition cost
K_F	€	Piece cost according to machine hour rate calculation
K_{FE}	€	Prime manufacturing cost
K_{FO}	€	Consequential cost
K_{LH}	€/h	Labor hour rate
K_{MH}	€/h	Machine hour rate
K_{ML}	€/h	Machine and labor hour rate
K_{VO}	€	Preparation cost
R	-	Output ratio between double and single workspace multi-technology platform

RL_{T1}	%	Relative likelihood of technology 1
RL_{T2}	%	Relative likelihood of technology 2
R_{max}	-	Maximum output ratio between double and single workspace multi-technology platform
T	SCD	Reference period
$T_{av,MT}$	min/SCD	Available capacity of machine tool
$T_{av,WS}$	min/SCD	Available capacity of work station
$T_{av,OP}$	min/SCD	Available capacity of operator
$T_{ef,OP}$	min/SCD	Effective capacity of operator
T_{max}	days	Maximum available time for amplification
$T_{op,MT}$	min/SCD	Operation time of a machine tool during reference period
$\hat{T}_{op,MT}$	min/SCD	Maximum operation time of a machine tool during reference period
U_m	-	Mean utilization of work station
$U_{m,max}$	-	Maximum mean utilization of work station
U_{T1}	%	Utilization of technology resource 1
U_{T2}	%	Utilization of technology resource 2
U_{Tm}	%	Mean utilization of technology resources
U_{WS}	%	Utilization of workspace
V	€	Value creation

$a_{\gamma,d,MT}$	-	Direct production coefficient between consumable γ and output quantity
$a_{\gamma,i,MT}$	-	Indirect production coefficient between consumable γ and output quantity
a_{MT}	-	Availability of machine tool
$\hat{c}$	€	Piece cost
c_d	€	Direct cost
$c_{con,d}$	€	Direct cost of consumable γ
$c_{con,i}$	€	Indirect cost of consumption per machine tool
c_{MT}	€	Cost per machine tool
$c_{MT,D}$	€	Depreciation cost per machine tool

$c_{MT,I}$	€	Imputed interest cost per machine tool
$c_{MT,M}$	€	Maintenance cost per machine tool
$c_{MT,O}$	€	Occupancy cost per machine tool
c_{oper}	€	Operator cost per machine tool
$c_{v,d}$	€	Variable direct cost
$c_{v,i}$	€	Variable indirect cost per machine tool
$c_{v,i,1WS}$	€	Variable indirect cost of single workspace multi-technology platform
$c_{v,i,2WS}$	€	Variable indirect cost of double workspace multi-technology platform
$c_{v,i}^{DF}$	€	Variable indirect cost of direct functions per machine tool
$c_{v,i}^{IF}$	€	Variable indirect cost of indirect functions per machine tool
$\hat{c}_{v,i}$	€	Variable indirect piece cost of manufacturing system
f_l	-	Workload fraction at l-th stage of transformation process
f_{max}	-	Workload fraction at bottleneck machine
$f_{p,red}$	-	Processing time reduction factor
i_u	-	Intensity of usage
m	qty.	Lot size
m_μ	qty.	Mean lot size
m_σ	qty.	Standard deviation of lot size
n	qty.	Workpiece complexity
n_μ	qty.	Mean workpiece complexity
n_σ	qty.	Standard deviation of workpiece complexity
o	qty.	Number of orders
$o_{crit,MT,l}$	qty.	Maximum number of orders machinable at l-th stage of the transformation process during reference period
p_{MT}	-	Failure probability of machine tool
q_γ	€/qty.	Factor price of consumable γ
$r_{\gamma,l}$	qty.	Consumption of consumable g during reference period

t	days	Time
t_c	min	Tool engagement time
t_{co}	min	Changeover time
$t_{co,\mu}$	min	Mean changeover time
$t_{co,\sigma}$	min	Standard deviation of changeover time
t_{cyc}	min	Cycle time per workpiece
t_e	min	Piece time according to the machine hour calculation
t_{er}	min	Personal recovery time
t_h	min	Primary processing time
t_{io}	min	Interoperation time
t_{jog}	min	Jogging time
t_m	min	Machining time
t_n	min	Secondary processing time
t_{op}	min	Operation time
t_p	min	Processing time
$t_{p,\mu}$	min	Mean processing time
$t_{p,\sigma}$	min	Standard deviation of processing time
t_{p1}	min	Processing time with technology resource 1
t_{p2}	min	Processing time with technology resource 2
t_t	min	Tool exchange time
t_{tp}	min	Throughput time
t_{tr}	min	Transportation time
t_v	min	Additional time
t_{wbp}	min	Waiting time before processing
t_{wdp}	min	Waiting during processing
t_{wc}	min	Workpiece change time
v	€/qty.	Value creation per workpiece
x	qty.	Output quantity in terms of features
x_{be}	qty.	Break-even output quantity
x_{crit}	qty.	Maximum output during reference period
y	qty.	Number of workpieces

ΔC_{conv}	€	Cost for amplification of conventional manufacturing system
ΔC_{flex}	€	Cost for adding flexibility to machine tool
$\Delta C_{sys,2WS}$	€	Additional cost for second workspace
$\Delta C_{sys,TR}$	€	Additional cost for technology resource
$\Delta C_{sys,TU}$	€	Additional cost for traveling unit
$\Delta c_{v,d}$	€	Variable direct cost difference between segregated and integrated manufacturing system
$\Delta C_{v,i}$	€	Variable indirect cost difference between integrated and segregated manufacturing system; Measure for the monetary synergy effect of manufacturing technology integration
$\Delta \tau_{co}$	min	Characteristic difference between changeover times of segregated and integrated manufacturing system
$\Delta \tau_{p}$	min	Characteristic difference between processing times of segregated and integrated manufacturing system
$\Delta t_{p,IMS,\%}$	%	Required, percentagewise reduction of processing time
$\Delta t_{p,mti}$	min	Required reduction of processing time by means of manufacturing technology integration
Δt_{op}	min	Operation time difference between segregated and integrated manufacturing system; Measure for the temporal synergy effect of manufacturing technology integration
$\Delta \tau_{wc}$	min	Characteristic difference between workpiece change times of segregated and integrated manufacturing system
Δv	€	Value difference between integrated and segregated manufacturing system
$\alpha_{c,strong}$		Inclination of value creation function according to the weak condition of absolute profitability
$\alpha_{c,weak}$		Inclination of value creation function according to the weak condition of absolute profitability
$\chi_{v,i,IMS}$	€	Variable indirect cost threshold
γ		Consumable

λ	days	Time parameter
μ_{abs}	qty.	Absolute lot size threshold
μ_{rel}	qty.	Relative lot size threshold
ν	qty.	Ratio of $\Delta\tau_{wc}$ and $\Delta\tau_p$
π	€	Profitability
π_{conv}	€	Profitability of conventional manufacturing system
π_{flex}	€	Profitability of flexible manufacturing system
ρ		Reduction factor
ρ_l	-	Mean utilization of l-stage of transformation process
τ_{op}	-	Operation time ratio between integrated and segregated manufacturing system
τ_{tr}	-	Ratio between transportation time and operation time in segregated manufacturing system
τ_{wdp}	-	Ratio of waiting time during processing and operation time
ω	-	Operation time ratio
ξ	qty.	Number of manufacturing technologies
ψ	-	Denominator of characteristic μ_{rel}

1WS		Subscript “Single workspace multi-technology platform”
2WS		Subscript “Double workspace multi-technology platform”
AEE		Absolute economic efficiency
AP		Absolute profitability
Config_1		Subscript “Double workspace multi-technology platform of configuration 1”
Config_2		Double workspace multi-technology platform of configuration 2
conv		Subscript “Conventional manufacturing system”
flex		Subscript “Flexible manufacturing system”
IMS		Subscript “Integrated manufacturing system”
MTP		Multi-technology platform

REE	Relative economic efficiency
RP	Relative profitability
SCD	Shop calendar days
SMS	Subscript “Segregated manufacturing system”

1 Deutsche Kurzzusammenfassung

Die vorliegende Dissertation behandelt das Thema „Wirtschaftlichkeit von Fertigungstechnologieintegration“. Fertigungstechnologieintegration bezeichnet ein Gestaltungsparadigma für Werkzeugmaschinen, das die Steigerung der Anzahl an Fertigungstechnologien auf einer Werkzeugmaschine zum Ziel hat. Eine Werkzeugmaschine, auf der mehr als eine Fertigungstechnologie ausführbar ist, wird als Multitechnologieplattform bezeichnet. Mehrere Multitechnologieplattformen bilden ein integriertes Fertigungssystem. Demgegenüber bestehen segregierte Fertigungssysteme ausschließlich aus Eintechnologiewerkzeugmaschinen.

Eine Multitechnologieplattform besitzt zwar das gleiche Funktionsspektrum wie ein entsprechendes segregiertes Fertigungssystem. Jedoch lässt sich in einer Multitechnologieplattform mit einem Arbeitsraum nur ein Werkstück bearbeiten, während auf den Werkzeugmaschinen des segregierten Fertigungssystems mehrere Werkstücke gleichzeitig bearbeitet werden können. Folglich besitzt eine einzelne Multitechnologieplattform eine geringere Produktivität als ein segregiertes Fertigungssystem.

Auf Grund der unterschiedlichen Produktivität ist für einen Wirtschaftlichkeitsvergleich von integrierten und segregierten Fertigungssystemen die Konfiguration des Fertigungssystems, das heisst die Parallelisierung von Werkzeugmaschinen über der Stückzahl, zu beachten. Der klassische Ansatz zur Bestimmung der Wirtschaftlichkeit von Werkzeugmaschinen, die Maschinenstundensatzrechnung, vernachlässigt jedoch die Konfiguration des Fertigungssystems und die produzierbaren Stückzahlen. Die Randbedingungen ökonomischer Produktion von integrierten Fertigungssystemen lassen sich mithin nicht auf Basis der Maschinenstundensatzrechnung ermitteln.

Das primäre Ziel dieser Arbeit lag daher in der Modellierung der Randbedingungen ökonomischer Produktion von integrierten Fertigungssystemen im Vergleich zu segregierten Fertigungssystemen.

Zur Modellierung der Randbedingungen ökonomischer Produktion von integrierten Fertigungssystemen im Vergleich zu segregierten Fertigungssystemen wurde in der Arbeit erstmals die Produktions-, Kosten-, und Warteschlangentheorie herangezogen. Es erfolgte eine mathematische Modellierung der Effizienzkriterien Produktivität, Profitabilität und Durchlaufzeit in Abhängigkeit von maßgeblichen Einflussfaktoren wie den Prozesszeiten, Kosten, der Produktkomplexität und den Losgrößen. Durch Gleichsetzen der Effizienzkriterien von integrierten und segregierten Fertigungssystemen konnten Isoquanten, das heisst Kurven gleicher Produktivität, Profitabilität oder Durchlaufzeiten, hergeleitet werden. Anhand der Isoquanten ließen sich Gebiete höherer Produktivität und Profitabilität sowie geringerer Durchlaufzeiten in Abhängigkeit von den Einflussfaktoren voneinander abgrenzen. Auf diese Weise wurde eine mathematische Darstellung der Randbedingungen abgeleitet, ab denen ein integriertes Fertigungssystem wirtschaftlicher als ein segregiertes Fertigungssystem ist. Die wesentlichen Erkenntnisse werden im Folgenden an einem vereinfachten Beispiel illustriert.

Abbildung 1.1 zeigt typische Durchlaufelemente integrierter und segregierter Fertigungssysteme. In Betracht gezogen wurde für die Abbildung die Fertigung von rotationssymmetrischen Wellen, die gedreht und geschliffen werden. Durch Fertigungstechnologieintegration entfallen Einspann- und Transportvorgange, so dass ein temporaler Synergieeffekt entsteht und die Durchlaufzeit integrierter Fertigung geringer ist als die Durchlaufzeit segregierter Fertigung.

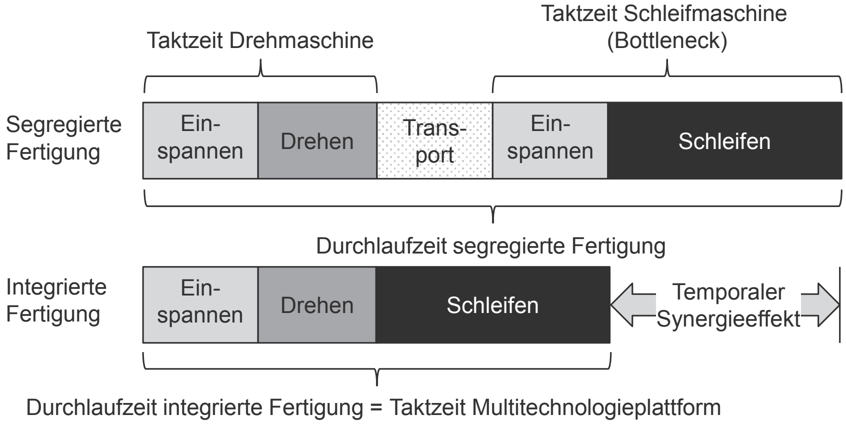


Abbildung 1.1: Durchlaufelemente von integrierten und segregierten Fertigungssystemen

Für die Produktivität des Fertigungssystems ausschlaggebend ist nicht die Durchlaufzeit, sondern die Taktzeit. Die Produktivität des segregierten Fertigungssystems wird durch die größte Taktzeit, im Beispiel durch die Taktzeit der Schleifmaschine (Bottleneck) festlegt. Obwohl ein erheblicher temporaler Synergieeffekt vorherrscht, ist die Produktivität integrierter Fertigung im Beispiel geringer als die Produktivität segregierter Fertigung.

Der Vergleich der Maschinen- und Lohnkostensätze K_{ML} in Abbildung 1.2 rechts zeigt, dass ein monetärer Synergieeffekt durch Fertigungstechnologieintegration erzielt wird, da die Kosten der Multitechnologieplattform ($K_{ML,MTP}$ = 100 €/h) geringer sind als die kumulierten Kosten der Dreh- und Schleifmaschine ($K_{ML,SMS}$ = 120 €/h). Der monetäre Synergieeffekt basiert beispielsweise darauf, dass für kleine Stückzahlen bei gleicher Funktionalität im integrierten Fertigungssystem nur ein Maschinenbett und eine Maschinensteuerung erforderlich sind, während das segregierte Fertigungssystem mehrere Maschinenbetten und –steuerungen beinhaltet.

Überschreitet die zu produzierende Stückzahl die Produktivitätsgrenze eines Fertigungssystems, so ist dessen Konfiguration durch Parallelisierung von Maschinen sukzessive anzupassen. Die Anpassung der Konfiguration des Fertigungssystems führt zu einem sägezahnartigen Verlauf der Stückkosten über der Stückzahl, siehe Abbildung 1.2.

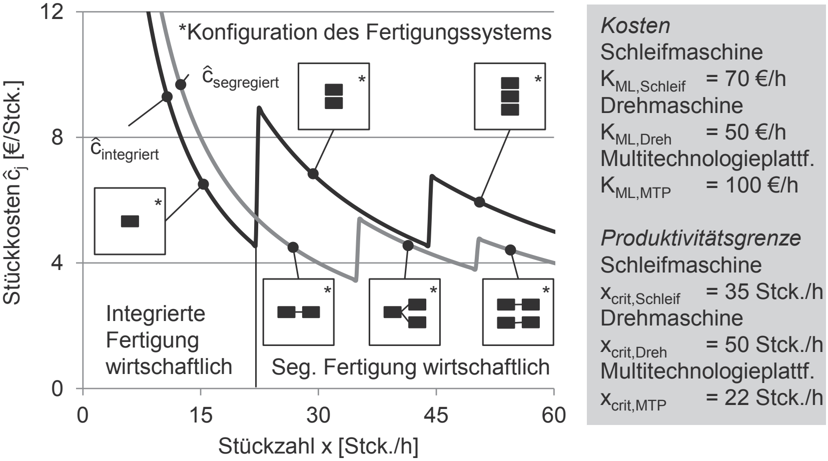


Abbildung 1.2: Stückkosten integrierter und segregierter Fertigung über der Stückzahl

Für kleine und große Stückzahlen lassen sich aus dem Stückkostenverlauf zwei unterschiedliche Kriterien für die Wirtschaftlichkeit von Fertigungstechnologieintegration festmachen. Für kleine Stückzahlen unterhalb der Produktivitätsgrenze einer Multitechnologieplattform $x_{\text{crit,MTP}}$ ist Fertigungstechnologieintegration wirtschaftlich, wenn die Maschinen- und Lohnkosten einer Multitechnologieplattform geringer sind als die kumulierten Maschinen- und Lohnkosten der Eintechnologiewerkzeugmaschinen. Für große Stückzahlen ist Fertigungstechnologieintegration wirtschaftlich, wenn die Maschinen- und Lohnkosten bezogen auf die Produktivität einer Multitechnologieplattform geringer sind als die kumulierten Maschinen- und Lohnkosten bezogen auf die Produktivität der Eintechnologiewerkzeugmaschinen. Da eine Multitechnologieplattform in der Regel eine geringere Produktivität als die Bottleneckmaschine des segregierten Fertigungssystems besitzt, sind die Anforderungen an die Wirtschaftlichkeit von Fertigungstechnologieintegration für kleine Stückzahlen geringer als für große Stückzahlen. Dementsprechend sollte Fertigungstechnologieintegration insbesondere für kleine Stückzahlen unterhalb der Produktivitätsgrenze der Multitechnologieplattform in Betracht gezogen werden.

In der Dissertation wurde weiterhin gezeigt, dass sich die Produktivität einer Multitechnologieplattform durch die Installation eines zweiten Arbeitsraums steigern lässt. Bei einer Multitechnologieplattform mit zwei Arbeitsräumen werden die Fertigungstechnologieressourcen mit einer Transporteinheit ausgestattet, so dass diese in beide Arbeitsräume eingreifen können. Auf Basis von Diskrete-Ereignis-Simulationen wurde gezeigt, dass der Produktivitätsgewinn des zweiten Arbeitsraums vom relativen Anteil der beiden Fertigungstechnologien an der Bearbeitungsaufgabe abhängt. Die Installation eines zweiten Arbeitsraums auf einer Multitechnologieplattform führt zwar zu einer Erhöhung der Produktivität, geht jedoch mit einer Steigerung der Maschinenkosten einher. In Abhängigkeit von der konkreten Erhöhung der Maschinenkosten sind Multitechnologieplattformen mit zwei Arbeitsräumen vor allem für Stückzahlen unterhalb ihrer Produktivitätsgrenze und oberhalb der Produktivitätsgrenze von Multitechnologieplattformen mit einem Arbeitsraum wirtschaftlich relevant, da in diesem Stückzahlbereich Multitechnologieplattformen mit einem Arbeitsraum parallelisiert werden müssen.

Für die Gestaltung von Fertigungssystemen unter volatilen Randbedingungen lassen sich zwei Strategien unterscheiden. Bei flexibler Strategie werden in Multitechnologieplattformen mehr Funktionen integriert als das Fertigungssystem zum Planungszeitpunkt benötigt, um auf spätere Änderungen der Anforderungen ohne Verzögerung reagieren zu können. Bei konventioneller Strategie werden Eintechnologiewerkzeugmaschinen akquiriert, deren Funktionen den aktuellen Anforderungen genau entsprechen. Bei einer Änderung der Anforderungen müssen bei konventioneller Strategie die Funktionen nachträglich erweitert werden, was zu einer Zeitverzögerung und einer Erhöhung der Kosten führt. Die relative Wirtschaftlichkeit der beiden Strategien hängt davon ab, wie groß die Wahrscheinlichkeit ist, dass sich die Funktionsanforderungen ändern sowie von der Zeit, die zur Verfügung steht, um nachträglich Eintechnologiewerkzeugmaschinen zu akquirieren. In der Dissertation wird auf Basis eines mathematischen Effizienzmodells gezeigt, dass die flexible Strategie basierend auf Multitechnologieplattformen wirtschaftlich ist, wenn wenig Zeit für nachträgliche Änderungen des Funktionsumfangs des Fertigungssystems zur Verfügung steht sowie, wenn die Wahrscheinlichkeit einer konkreten Änderung der Funktionsanforderungen groß ist.

In der Dissertation wurde die Wirtschaftlichkeit von Fertigungstechnologieintegration auf Basis eines entscheidungstheoretischen Wissenschaftsansatzes unter Verwendung von quantitativen Modellen der Produktions-, Kosten- und Warteschlangentheorie betrachtet. Zukünftige Forschung sollte auf Basis eines systemtheoretischen Ansatzes erfolgen, indem der Einfluss von Fertigungstechnologieintegration im Zusammenspiel aller Systemelemente auf die Ziele der Produktion im konkreten Produktionsumfeld empirisch untersucht wird.

2 Introduction and modus operandi

2.1 Introduction

Manufacturing industries face an increasingly turbulent market environment. The key challenges are individualization of demand, decreasing forecastability of production volumes, and large product complexity through ever-increasing variant diversity. Market pressure leads to shorter product life cycles while customers' demands rise with regard to product and service quality, lead time, and price. Furthermore, globalization increases the number of potential competitors significantly, thus fostering the intensity of rivalry in market segments

Under such market conditions, manufacturing industries are forced to scrutinize their present way of manufacturing goods carefully. Alternative manufacturing techniques must be evaluated continuously and almost immediately companies need to decide whether or not to adjust to newly arising manufacturing system paradigms. While companies that are successfully applying superior paradigms may gain a significant market advantage improper paradigms hinder market success since huge capital commitment is involved.

Manufacturing technology integration is one of such production paradigms that have received great attention recently. Integrated manufacturing systems, so-called multi-technology platforms, are machine tools that may execute a variety of manufacturing technologies. Thus, a single multi-technology platform may substitute a system of two or more conventional single-technology machine tools.

Machine tool builders claim that manufacturing technology integration brings about a variety of benefits such as shorter processing and throughput times, compare [KUTT07b] and [FEIN11]. Furthermore, integrated manufacturing systems are said to be more efficient than conventional machine tools if the geometry to cut is "sufficiently" complex, compare [FILI13]. However, producers experience *practical problems* if they intend to evaluate the benefits of manufacturing technology integration because no reference model to objectively compare the economic efficiency of multi-technology platforms to conventional machine tools has been defined so far.

This thesis reflects the advantageousness of multi-technology platforms in comparison to conventional single-technology machine tools through the study of mathematical and simulation models. The goal is to derive the conditions under which integrated manufacturing systems are economically efficient and thus contribute to the evaluation of the manufacturing system paradigm "manufacturing technology integration".

2.2 Modus operandi

Figure 2.1 presents a taxonomy of sciences introduced by Ulrich and Hill which will be applied to classify the type of research depicted in this thesis, compare [ULRI76a]. According to the scheme, engineering and business administration may be regarded as applied sciences with pragmatic goals in contrast to fundamental sciences following epistemic goals. Applied sciences focus on the analysis of decision alternatives:

e.g. this thesis elucidates the question whether or not manufacturing technology integration may enhance the performance of a manufacturing system.

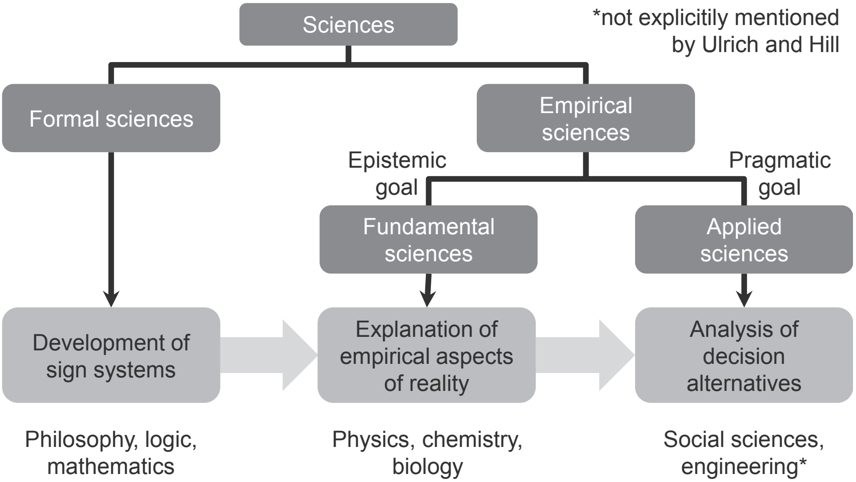


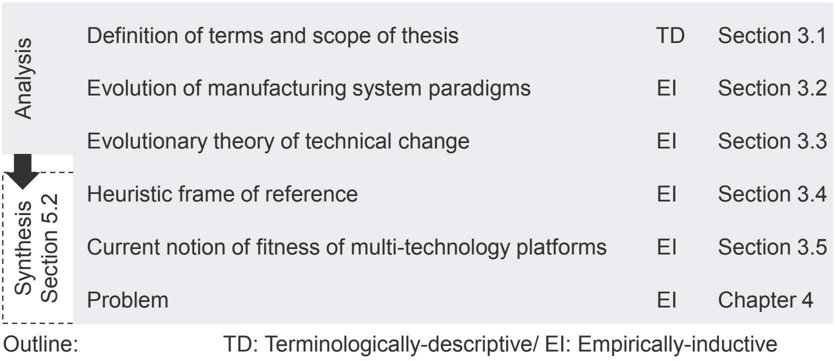
Figure 2.1: Classification of sciences according to Ulrich and Hill [ULRI76a]
Klassifikation der Wissenschaften nach Ulrich und Hill

According to Ueda et al. the underlying methodology of engineering consists of analysis followed by synthesis. During analysis knowledge about existing things is acquired, whereas the generation of new knowledge or artefacts takes place through synthesis [UEDA09, p. 685; UEDA08, UEDA01]. This strict dichotomization was applied to divide the thesis into an analytic part (chapter 2 and 3) and a synthetic part (chapter 5-7).

The analytic part aims at translating the practical problem outlined in the introduction into a theoretical problem. According to Kubicek heuristic frames of reference may serve as depictions of the theoretical problem and should embody the relevant quantities, relations, and mechanisms of the matter under study [KUBI77, p. 18 et seq.]. To construct a frame of reference with a great heuristic potential Kubicek suggests that the researcher should bring his presuppositional knowledge to mind which is mostly defined by academic training and professional socialization. Furthermore, the researcher should extent his preliminary perspective by an intensive study of literature, close contact to persons concerned with the practical problem, as well as aspire to an intensive interchange with other scientist in the field of study [KUBI77, p. 22 et seq.].

The author's initial perspective was coined by his studies in mechanical engineering and business administration as well as his professional career at the Laboratory for Machine Tools and Production Engineering WZL. The author was firstly confronted with practical problems in economic efficiency of manufacturing technology integration during a bilateral research project with a German machine tool builder. In the course of his employment at WZL, further exchange of thoughts with machine tool builders as well as producers lead to the assimilation into industry's perspective on manufacturing technology integration. An enhancement of perspective took place through the correspondence with a Professor in the field of philosophy who had lectured philosophy of technology at RWTH Aachen University. Based on his suggestion, the heuristic frame of reference was largely influenced by evolutionary theories of technical change, see figure 2.2. The author exchanged ideas with other manufacturing engineers in particular through his membership in the research group "Multi-Technology Production Systems" within the DFG funded Cluster of Excellence "Integrative Production Technology for High-Wage Countries". Moreover, the research progress was documented closely over the last years by publications in international journals and participations in conferences sponsored by the International Academy for Production Engineering (CIRP).

First, section 3.1 presents a definition of terms and narrows down the scope of this thesis. This part is of terminologically-descriptive nature, see figure 2.2. Second, the empirically-inductive literature study depicts currently prevailing perspectives on the evolution of manufacturing system and machine tool design paradigms, see section 3.2. Section 3.3 recapitulates evolutionary theory of technical change which provides a perspective on the origin of manufacturing technology integration. This perspective is captured within the heuristic frame of reference in section 3.4. Based on the heuristic frame of reference the current notion of fitness of multi-technology platforms will be discussed in section 3.5. In section 4 the problem which will be addressed by the research depicted in the synthetic part of this thesis is outlined. The synthetic part of the thesis will be outlined in section 5.2.



Definition of terms and scope of thesis	TD	Section 3.1
Evolution of manufacturing system paradigms	EI	Section 3.2
Evolutionary theory of technical change	EI	Section 3.3
Heuristic frame of reference	EI	Section 3.4
Current notion of fitness of multi-technology platforms	EI	Section 3.5
Problem	EI	Chapter 4

Outline: TD: Terminologically-descriptive/ EI: Empirically-inductive

Figure 2.2: Modus operandi in analytic part of thesis
Vorgehensweise im analytischen Teil der Dissertation

3 State of the art in research and industry

3.1 Definition of terms and scope of thesis

3.1.1 Definition of terms

This thesis is entitled “Economic efficiency of manufacturing technology integration” and depicts research conducted within the scope of production engineering. The current section defines the key terms of the thesis through the creation of a *semantic field*. The discussion will be initiated from the terms present within the title and extended to unmentioned opposites.

The term “efficiency” refers to the expenditures required to achieve an intended purpose. Depending on the context diverse purposes may be distinguished, so-called efficiency criteria. The adjective “economic” indicates that the efficiency criteria emanate from the economic domain. Common economic efficiency criteria in the scope of production engineering are productivity, profitability, cost, throughput time, quality etc.

The Oxford dictionary defines “manufacturing” as the production of “goods on a large scale using machinery” [HORN11]. During the transformation of raw material into the final product diverse “manufacturing technologies” are applied to create the shape and the properties of the workpiece. DIN 8580 distinguishes six basic groups of manufacturing technologies: primary shaping, forming, cutting, joining, coating, and changing of properties [DIN03]. While the term “manufacturing technology” relates to the underlying physical or chemical principle of manufacturing, a “manufacturing process” describes a concrete manufacturing operation under defined boundary conditions.

Usually, only the execution of forming, cutting, and joining processes takes place on machine tools. However, some exceptions to this rule exist as roller burnishing belonging to the sixth group “changing of properties” may also be carried out on machine tools. Machine tools are elements of “manufacturing systems”. The CIRP encyclopedia for production engineering defines the term “manufacturing system” as being an “organization within the manufacturing industry for the production of products” [CIRP14].

Among others, Koren has shown how the design of manufacturing systems is guided by paradigms which evolve over the course of time [KORE10], see sections 3.2 and 3.3. In fact, “manufacturing technology integration” may be regarded as a particular design paradigm that guides the layout of manufacturing systems as well as the design of machine tools.

The term “integration” originates from the past participle of the Latin verb “integrare” which means “to make a whole”, compare [STOW11]. “Manufacturing technology integration” signifies that a machine tool is equipped with a functional spectrum which allows for the execution of two or more functionally distinct manufacturing technologies previously executed on two or more separate machine tools. A machine tool designed according to the manufacturing technology integration paradigm will be called a “multi-technology platform”. Furthermore, an integrated manufacturing system denominates a manufacturing system consisting of multi-technology platforms. Multi-technology platforms and integrated manufacturing systems embody the manufacturing technology integration paradigm.

The antonym of “integration” is “segregation”. The term “segregation” is broadly applied in sociology to describe attribute based separation phenomena of societal elements within an observation area. Within the scope of this thesis “manufacturing technology segregation” will denominate the contrary idea of “manufacturing technology integration” i.e. functionally distinct manufacturing technologies are executed on separate machine tools. These machine tools will be called single-technology machine tools. Single-technology machine tools are elements of “segregated manufacturing systems”.

3.1.2 Scope of thesis

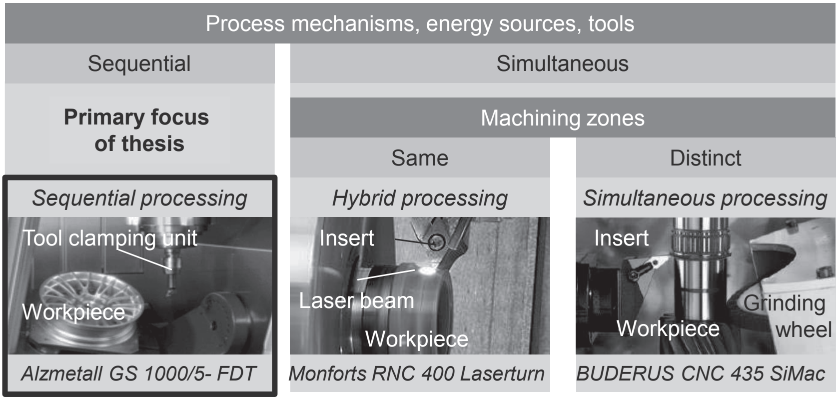
The scope of thesis may be outlined further by application of subject-related, process-related, and object-related differentiations, compare [RODE13, p. 5]. The subject-related differentiation delimits the group of addressees of this thesis. As emphasized above, manufacturing technology integration is a phenomenon discussed within the scope of production engineering and affects the layout of manufacturing systems as well as the design of machine tools. Hence, the addressees of this thesis are factory planers and machine tool designers concerned about optimizing the application of integrated manufacturing systems.

The process-related differentiation refers to the research approach and the methods applied to extend the knowledge about manufacturing technology integration. However, an ideal choice of research approach may only be made after analysis of the current state-of-the-art and definition of the exact research goal. Hence, the process-related differentiation in terms of research approach takes place in section 5.2.

Through object-related differentiation the objects under study are clarified. As outlined, manufacturing technology integration is an intellectual paradigm which manifests itself in the physical world of objects in a sense that it guides the layout of manufacturing systems as well as the design of machine tools. Hence, machine tools being the fundamental physical elements of manufacturing systems will be used as a reference for the object-related differentiation.

Figure 3.1 distinguishes execution modes of manufacturing processes with regard to a single workpiece. A comparable scheme was presented by Merchant and Dornfeld in 2005, compare [MERC05; BYRN03, p. 497]. Process mechanisms, energy sources, and tools may act sequentially or simultaneously on the workpiece. This thesis focusses primarily on sequential processing on integrated manufacturing systems because it is the most frequent type of manufacturing technology integration. However, based on the discussion of sequential processing some conclusions may be drawn with regard to process mechanisms, energy sources, and tools acting simultaneously on the workpiece.

Within the latter category two sub-types of manufacturing execution modes need to be distinguished with regard to the number of machining zones. The collaborative working group on “Hybrid Processes” within the International Academy for Production Engineering (CIRP) defined hybrid processing as “based on the simultaneous and controlled interaction of process mechanisms and/ or energy sources/ tools within the *same* machining zone having a significant effect on the process performance” [LAUW12]. Hybrid processing is not to be confused with simultaneous processing. As opposed to hybrid processing, process mechanisms, energy sources, and tools act in distinct machining zones in simultaneous processing. In the following three machine tools for sequential, hybrid, and simultaneous processing will be presented.

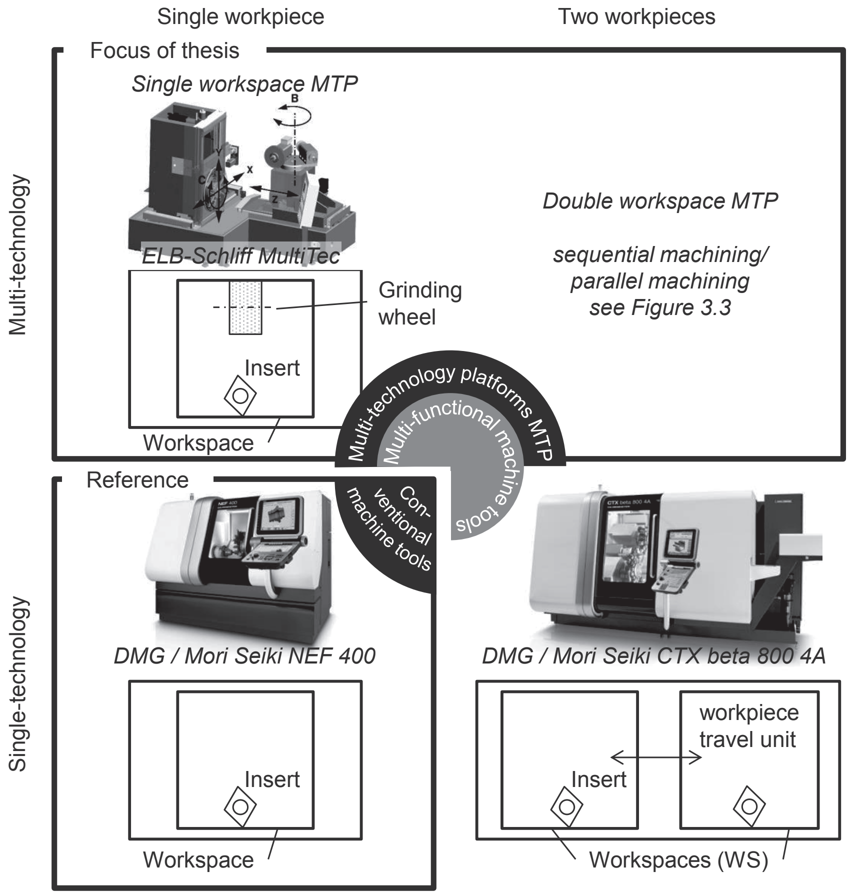


Source of pictures : [ARNT11; p. 325], [ARNT11; p. 334], [RAAB07; p. 15]

Figure 3.1: Execution modes of manufacturing process
Arten der Ausführung von Fertigungstechnologien

The “Alzmetall GS 1000/5-FDT” possesses a functional spectrum which allows for the sequential processing of workpieces by manufacturing technologies such as turning, milling, and grinding, compare [ARNT11]. The respective picture of the workspace of the machine tool in figure 3.1 depicts a workpiece as well as a tool clamping unit attached to the spindle which may clamp diverse tools sequentially. The “Monforts RNC 400 Laserturn” is a multi-technology platform which enables hybrid processing by laser assisted turning, compare [ARNT11; KLOC97]. Simultaneous processing may take place on the “BUDERUS CNC 435 SiMac”. This machine tool possesses two guideways in parallel to the workpiece spindle which enable the axial movement of grinding wheels, turrets equipped with diverse turning chisels, or roller burnishing tools. These tools may engage simultaneously with the workpiece from each side of the workpiece spindle as depicted in the respective picture in figure 3.1, compare [RAAB07, p. 15 et seq.].

Furthermore, this thesis distinguishes four types of machine tools which possess a functional spectrum to enable sequential processing of workpieces, see figure 3.2. The distinction takes place along the dimensions “number of manufacturing technologies” and “number of workpieces” that may be clamped and machined simultaneously. A “DMG / Mori Seiki NEF 400” is a “conventional” single-technology machine tool for turning operations on a single workpiece. Segregated manufacturing systems consisting of such single-technology machine tools will be used as a reference for the comparison of the paradigms “manufacturing technology integration” and “manufacturing technology segregation” in chapter 6.



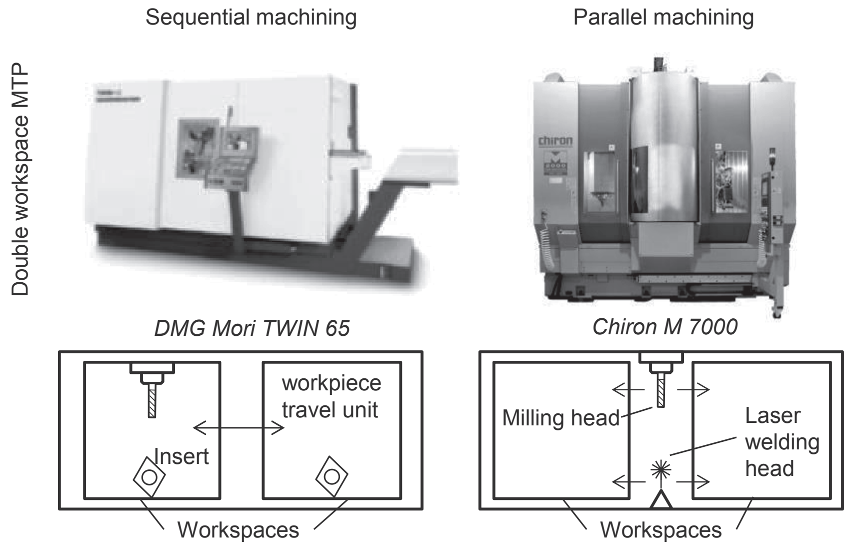
Source of pictures, upper: ELB-Schliff, lower: www.dmgmoriseiki.com

Figure 3.2: Classification of machine tools
Klassifizierung von Werkzeugmaschinen

The “DMG / Mori Seiki CTX beta 800 4A” may be considered to be a “multi-functional machine tool” because it possesses a second workpiece spindle, compare [MORI08, p. 738]. Due to the second workpiece spindle the machine tool is capable of simultaneously machining two workpieces by sequential processing through turning.The

"ELB-Schliff MultiTec" is a multi-technology platform since this machine tool provides a functional spectrum which enables the execution of more than a single manufacturing technology, compare [KUTT10a]. Multi-technology platforms may be considered to be a sub-category of multi-functional machine tools, compare [MORI08, p. 738]. The "ELB Schliff Multitec" is a "single workspace multi-technology platform" capable of performing sequential processing by diverse drilling, milling, grinding, and turning operations on a *single* workpiece.

Double workspace multi-technology platforms are capable of machining two workpieces simultaneously. Two types of double workspace multi-technology platforms may be distinguished, see figure 3.3.



Source of pictures: www.dmgmoriseiki.com, [ARNT11; p. 327]

Figure 3.3: Classification of double workspace multi-technology platforms
Klassifizierung von Doppelarbeitsraummultitechnologieplattformen

The turning center DMG Mori TWIN 65 machines workpieces sequentially in two workspaces. A certain number of machining operations takes place in workspace 1 before the *workpiece is passed* to workspace 2 and the machining continues. As soon as workspace 1 is free the machining of a new workpiece may begin. The Chiron M 7000 possesses a laser welding and a milling head which may enter either workspace. Workpieces remain in the same workspace but *technology resources travel* between the workspaces. Hence, double workspace multi-technology platforms enhance the productivity in comparison to single workspace multi-technology platforms. The economic efficiency of single workspace multi-technology platforms will be discussed in chapter 6, while economic efficiency of double workspace multi-technology platforms is elucidated in chapter 7.

3.2 Evolution of manufacturing system paradigms

The current chapter gives an introduction to the evolution of manufacturing system paradigms in the past. Furthermore, it outlines two manufacturing system paradigms, reconfigurability and manufacturing technology integration, which are currently discussed for the design of machine tools. It is concluded that manufacturing technology integration possesses a greater degree of maturity than reconfigurable machine tools as diverse multi-technology platforms are already wide-spread in industry.

In production engineering research broad consensus prevails about the idea that manufacturing system paradigms are subject to evolution-like mechanisms, see [WARN93; WIEN94; ELMA08; TOLI10; ELMA12]. A key concept adapted from biology is the idea of “co-evolution” between markets, products, and manufacturing systems which was introduced to production engineering literature by Wiendahl in 1994, see [WIEN94] and compare [WALD92]. First, the role of time and boundary conditions in manufacturing related co-evolution will be illustrated by this section. Second, the development of manufacturing system paradigms for high-wage countries in the 21st century will be discussed.

Figure 3.4 illustrates co-evolution of markets, products, and manufacturing systems over the *course of time* as viewed by Koren, see [KORE10, p. 38]. Dedicated manufacturing lines designed to produce a single mass product in large quantities were most competitive during the era of mass production. According to Koren the “dedicated manufacturing paradigm” originates in Taylor’s “scientific management” and fitted societal needs characterised by suppliers’ markets until the oil crises of the 1970s. During the era of mass customization producers adapted to saturated markets in which customers based consumption decisions on quality and individualization by flexible manufacturing systems. Koren predicts the prolongation of this customization trend and anticipates that reconfigurable manufacturing systems are best suited to meet future challenges in manufacturing. [KORE10]

In Koren’s model, prevailing manufacturing system paradigms are always completely overthrown if subsequent paradigms fit better to newly arising market environments. However, such radical displacement of “species” seldom occurs neither in biology nor in technology, compare [GUTM89; MOKY90]. In fact, distinct *boundary conditions of production* might exist in parallel which foster alternative manufacturing paradigms at the same time.

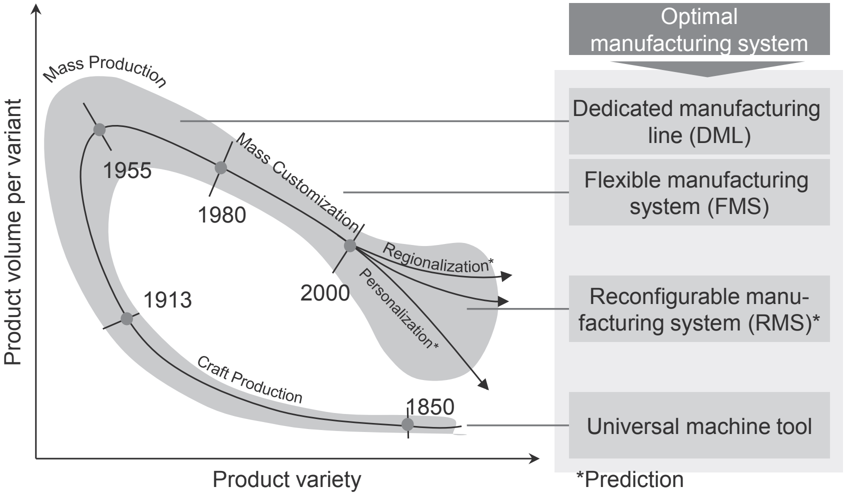
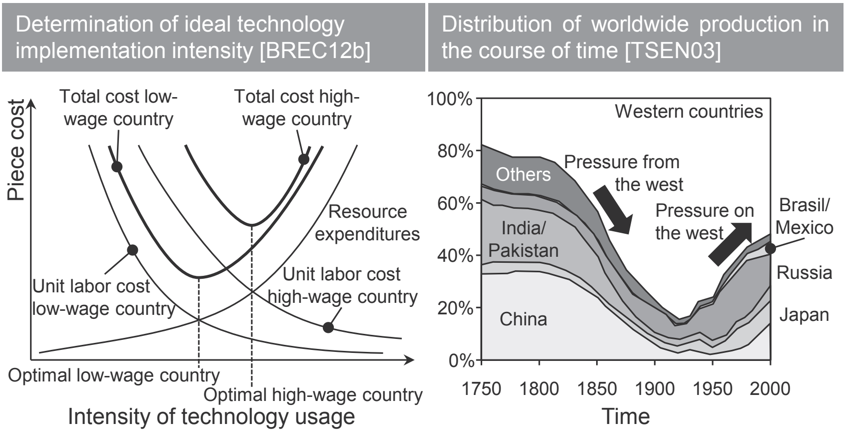


Figure 3.4: Market and society as drivers for new paradigms [KORE10, p. 38]

Märkte und Gesellschaft als Treiber neuer Paradigmen

The worldwide distribution of labor cost provides a prominent example of manufacturing paradigm co-existence as a consequence of distinct boundary conditions. Due to the low unit labor cost in a low wage country a significantly lower intensity of technology usage in production is required to minimize the piece cost, see left diagram in figure 3.5 and compare [BREC12b, p. 25]. Hence, craft and mass production still prevails in low wage countries and through the application of seemingly antiquated manufacturing paradigms large pressure is exerted on western countries, see right diagram in figure 3.5 and compare [TSEN03].

Western countries meet the pressure of low wage economies through increasingly focusing on the manufacture of individualized premium products, compare [BREC12b, p. 24]. However, this strategy stipulates manufacturing systems capable of almost immediate adaption to highly volatile customer demands, compare [CHRY06] cited by [WIEN07, p. 783].


Determination of ideal technology implementation intensity [BREC12b]

Distribution of worldwide production in the course of time [TSEN03]

Figure 3.5: Influence of boundary conditions on manufacturing paradigms

Einfluss der Randbedingungen auf Fertigungsparadigmen

Currently, mainly two distinct and to some extent contradictory paradigms are discussed with regard to the design of machine tools which will enable the competitiveness of manufacturing systems in such turbulent market environments. The first paradigm originates in a system theory's perspective on manufacturing. According to some authors, future manufacturing systems are to be designed according to the "changeability" paradigm, compare [WIEN07]. Wiendahl et al. define changeability as the "characteristics to accomplish early and foresighted adjustments of the factory's structures and processes on all levels to change impulses economically", compare [WIEN07, p. 785]. Wiendahl discerns five structuring levels of manufacturing systems which are associated to five product levels taking on the idea of co-evolution. Each level refers to a distinct class of changeability, compare [WIEN02]. On the level of work stations and cells, hence, machine tools the "changeover ability" and "reconfigurability" is regarded to be the key so-called "enabler" of changeable manufacturing systems, compare [WIEN07]. Thus, as a consequence of the system theory's perspective on manufacturing and the changeability paradigm "reconfigurable machine tools" have been discussed broadly for more than a decade, compare [LAND01; ABEL06; MOON06; MOON02; MOON00]. In short, reconfigurable machine tools will allow for the *exchange of functions* such that machines may serve diverse purposes over their life cycle.

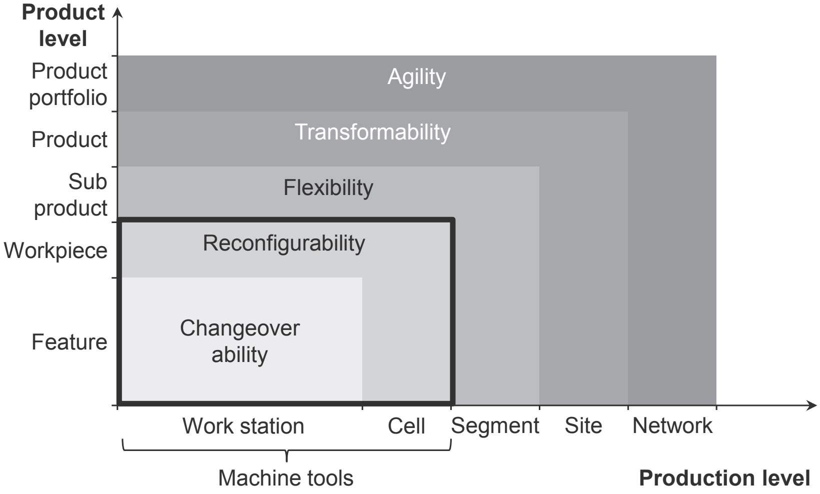


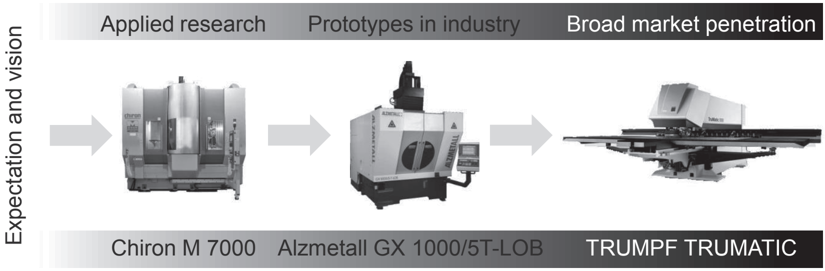
Figure 3.6: Classes of factory changeability [WIEN07, p. 785]
Wandlungsfähigkeitsklassen

However, while the changeability paradigm has already been applied successfully to the design of reconfigurable assembly systems, reconfigurable machine tools are not yet broadly used in industry, compare [WIEN07, p. 789 et seq.]. Firstly, the initial costs of reconfigurable machine tools are higher than those of conventional single-technology machine tools, compare [ABEL05]. Secondly, the maturity of the technology is still low, compare [ELMA07]. Technological hurdles exist with regard to the kinematic viability, structural stiffness, and geometric accuracy, compare [YIGI02; LAND01; LAND06] cited from [WIEN07, p. 789]. Besides the mechanical problems, Pasek names challenges such as defining part families, control system design, and system integration, compare [PASE06]. Although attempts have been made to overcome these hurdles, compare [MOON00; MOON02], no systematic approach exists so far to design reconfigurable machine tools, compare [MOON06]. Hence, it may be concluded that the changeability paradigm has not yet proven its viability with regard to design of machine tools.

The second machine tool design paradigm claiming to enable competitiveness of future manufacturing systems is manufacturing technology integration. Manufacturing technology integration contradicts the idea of changeability as it postulates the integration of *additional functions* rather than allowing for the exchange of functions, compare [MORI08]. Hence, manufacturing technology integration may be regarded as an interpretation of the “flexible manufacturing” paradigm that promotes the functional enhancement of machine tools.

The manufacturing technology integration paradigm is fostered in particular by research communities directly concerned with the design and operation of machine tools. Moriwaki's CIRP keynote paper from 2008 entitled "multi-functional machine tools" may be regarded as strong evidence for this hypothesis. Naturally, such technology driven research communities put less emphasis on a system theory's perspective on the paradigm driving the technological advance but focus on technological feasibility. While the manufacturing system's perspective runs at risk of facing currently insurmountable technological obstacles in the design of machine tools, the machine tool driven perspective might ignore the importance of economic justification of ever increasing technological complexity.

The manufacturing technology integration paradigm possesses a greater degree of maturity than the changeability paradigm as diverse multi-technology platforms are broadly applied in industry, some of which for decades, compare [ARNT11]. Brecher and Eppler discern three degrees of market penetrations in [ARNT11, p. 323]. Based on expectations and visions, fundamental and applied research is carried out in technology niches, see figure 3.7, taking into account industry's demand. If a promising design has emerged industry is willing to evaluate the viability of prototypes. However, a considerable number of diverse multi-technology platforms have been deployed successfully in industry already *clearly illustrating the viability of the manufacturing technology integration paradigm*. A remarkable multi-technology platform was developed by Trumpf GmbH & Co. KG in 1979 combining punching and laser cutting, see right picture in figure 3.7. Punching enables high productivity whereas laser cutting may account for great geometrical flexibility, compare [ARNT11].



Source of pictures: [ARNT11; p. 317 et seq.]

Figure 3.7: Market readiness of multi-technology platforms in 2011 [ARNT11]
Marktreife von Multitechnologieplattformen in 2011

Moriwaki distinguishes four basic "families" of multi-technology platforms with broad market penetration based on the type of single-technology machine tool they have descended from, compare [MORI08, p. 740 et sqq.]. Multi-functional turning machines may perform e.g. external milling or drilling operations thus enabling the manufacture of complex parts with square features, compare [MORI08, p. 737]. Moriwaki presents a survey of manufacturing technologies integrated into turning machines in [MORI06, p. 4]. In turn, multi-functional milling machines may carry out e.g. vertical turning or grinding operations apart from milling, see Alzmetall GS 1000/5- FDT in figure 3.1 and compare [MORI08, p 749; ARNT11]. Parallel kinematic machines were enhanced for milling, turning, riveting, and forming by machine tool builders, compare [WECK02, p. 675; MORI08]. Lastly, Moriwaki points out the importance of manufacturing technology integration to the field of precision and ultraprecision machining, which enables meeting ever higher accuracy requirements. In this field, “typical machining functions required are turning, fly cutting, planning, milling and grinding”, compare [MORI08, p. 743].

The market success of multi-technology platforms encourages research and machine tool builders to create “technology niches” to advance the design of integrated manufacturing systems. The research conducted within these niches is coined by the search for a “dominant design”. A very demonstrative illustration of this search was presented by Sato who studied 2160 distinct configurations of vertical milling centers, compare [SATO06].

Moriwaki names key components and supporting technologies of multi-technology platforms, compare [MORI08, p. 743]. Of course, linear and rotary feed drives as well as high speed spindles are fundamental components of multi-technology platforms which enable an accurate and fast machining operation, compare [MORI08, p. 743; ALTI11; ABEL10]. But the robust and efficient utilization of multi-technology platforms depends on the software and control technology, too, compare [ABEL10, p. 743]. The CAM software must translate the CAD-data into tool paths which is more challenging the greater machine tool complexity becomes, compare [BREC13, p. 449]. Furthermore, open control architecture as well as NC program verification and collision avoidance represent key supporting technologies to increase the flexibility and robustness of multi-technology platforms, compare [MORI08, p. 744].

Manufacturing technology integration is an emerging paradigm for the design of machine tools. In the following the mechanisms of paradigm creation and its acceptance by technology users are discussed based on evolutionary theory of technical change. The goal is to identify shortcomings and problems which hinder the success of manufacturing technology integration.

3.3 Evolutionary theory of technical change

Evolutionary theory of technical change is a field of research originating in evolutionary economics and philosophy of technology. Evolutionary economics breaks with mechanistic analogies of market equilibria and rationality assumptions cumulated within the concept of the so-called “homo economicus”, compare [DOSI94, p.153 et seq.]. Although Darwinian evolutionary theory may be regarded as the point of origin of evolutionary economics, nowadays, *analogies with biology* are “pursued with great caution because they *may restrict our thinking*”, compare [SCHO07, p. 614]. In fact, Nelson introduced the idea of a *general theory of evolution* which may assume distinct characteristics if applied to a biological or technological background, see [NELS95, p. 54]. First, this section elucidates principal building blocks of a general evolutionary theory before outlining differences between biological and sociotechnical application. Lastly, the role of niches in evolutionary theories of technical change will be clarified.

Dosi and Nelson identify four principal building blocks of a general evolutionary theory. They discern the fundamental units of selection, a mechanism of linking the fundamental units of selection to physical entities, as well as mechanisms of variation and selection, see [DOSI94, p. 155]. In biology, genes assume the role of fundamental units of selection whereas paradigms which store "shared engineering search heuristics, ways of defining problems, user preferences, expectations, product characteristics, skills, standards, and regulatory frameworks" preform the task of fundamental units in sociotechnical systems, compare [SCHO07, p. 609]. The genes or paradigms manifest themselves within the physical world through phenotypes, namely organisms or products, which are exposed to the actual environmental selection, compare [DOSI94, p. 155].

According to Campbell the key concept of Darwinian evolutionary theory can be summarized as "blind variations selectively retained", compare [CAMP60] cited by [ZIMA03; SCHO07, p. 607]. Genes are blind in a sense that they may neither influence the direction of variation nor anticipate the prospective fitness of the respective phenotypes. Biological mutations just occur and the fully independent selection environment determines which of the respective phenotypes are *viable*. Furthermore, biological evolution does not necessarily complicate organisms. The fitness of an organism within a selection environment may be increased through both, increasing complexity or through *performance-enhancing simplification*, compare [GUTM89, p. 50].

In technical evolution variations need not to be blind but may be influenced intentionally by technology actors, compare [SCHO07, p. 614]. Hence, besides Darwinian blind and undirected evolution, technology might be advanced by directed and thus *Lamarckian* evolution. The Lamarckian model of evolution was introduced by the French biologist Jean-Baptiste de Lamarck in 1809 and is fully discarded in biology due to the assumption that variation and selection are not independent, compare [LAMA09]. However, the model provides a suitable analogy to the way technology actors "anticipate on selection and work towards linkages between variations and selections" [SCHO07, p. 614].

In the Lamarckian view, the direction of technological advancement is determined through a *notion of fitness* which represents a *vague image* of the prospective product designed according to the technology paradigm within the selection environment. The notion of fitness is a mental model created by the technology actors which is pivoted on *expectations and beliefs* and evolves through *mistake-ridden leaning and discovery* as well as *selection mechanisms*, compare [SCHO07, p. 615; DOSI94]. Hence, any technology related research and development process should be closely accompanied by an advancement of the respective notion of fitness to enhance the viability of the technological paradigm. As any social selection environment may be regarded multi-facetted, a mature notion of fitness should account for *multiple selection criteria*, compare [SCHO07, p. 607].

The possibility of directed technical evolution bears an important consequence with regard to the magnitude of viable mutations that may occur. In biology, most evolutionists reject the idea of viable *macro mutations* and believe that significant changes in genes are an accumulation of micro mutations over long periods of time, compare [SCHO07, p. 610]. Gutmann argues that “the excessive enlargement of any structure (monstrosity) is prevented through (natural) selection”, compare [GUTM89, p. 45].

Mokyr elaborates on the role of macro mutations like multi-technology platforms in technology and presents broad indication that technological evolution may be partly governed by discontinuous and non-adaptive macro mutations of paradigms, compare [MOKY90, p. 295] cited from [SCHO07, p. 610]. In analogy to biology, Mokyr calls inventions based on macro mutations of technological paradigms “monstrosities” but adds the attribute “hopeful” which refers to the respective beliefs and expectations of technology actors, compare [MOKY90]. Macro inventions “are hopeful because they promise new technical and functional possibilities. They are monstrous because their early performance characteristics are typically low”, compare [SCHO07, p. 611]. Analogous to biology, the viability of a macro invention is determined through the selection environment. Mokyr emphasizes the unforeseeable nature of the sociotechnical selection environment by the following metaphor:

“Macro-inventions are seeds sown by individual inventors in a social soil. (...). The environment into which the seeds are sown is, of course, the main determinant of whether they will sprout.” [MOKY90, p. 299] cited from [SCHO07, p. 611]

Finally, diverse mechanisms through which a radical technological paradigm shift is provoked will be explored. In 2007 Schot and Geels presented a theory which discerns four patterns of paradigm emergence and emphasizes the role of niches, compare [SCHO07, p. 617 et seq.]. The *natural selection pattern* closely follows Darwinian evolutionary theory as successive micro mutations of paradigm within existing selection environments lead to the rise of a new technological species. The *pattern of punctuated equilibrium* describes the advent of viable inventions based on macro mutations of paradigms to prevailing selection environments carried by the sociotechnical regime. These inventions disturb the market equilibrium and provoke a rapid change in the notion of fitness of market actors, compare [SCHO07, p. 611]. *Market niche development* takes place in remote niches which are governed by selection criteria distinct from those present within the predominant sociotechnical regime. Market niche developments are initiated by micro or macro mutations which are amplified by “unique rules” of the respective niches. Subsequently, these rules trigger an independent development pathway which leads to the emergence of a new technological paradigm, compare [LEVI98] cited by [SCHO07, p. 612].

According to Schot and Geels the fourth pattern of paradigm creation takes place in proto-markets called *technology niches*. These niches are established by technology actors well in advance of market launch to test and develop new technologies. In most cases technology niches exist only for a limited amount of time because pilot projects concerned with advancing technology into a certain direction fail. However, sometimes viable macro inventions emanate from technology niches and “proceed through one of the three other mentioned patterns.” [SCHO07, p. 618]

Figure 3.8 depicts the interplay of a technology niche and the socio technical regime as perceived by Geels, compare [GEEL02, p. 1263; SCHO08, p. 546]. Technology niches foster a new paradigm based on expectations and visions. The product development process is accompanied by mistake-ridden learning processes which refine the respective notion of fitness until a dominant design emerges. However, even if a seemingly viable product is developed within the technology niche the actual competitiveness of the macro invention is determined by the present sociotechnical regime and the dynamic stability of the selection environment. Only during certain periods, so-called "windows of opportunity", the sociotechnical regime adjusts prevailing selection criteria and allows for macro inventions to flourish. [SCHO08, p. 547]

Schot and Geels recommend applying the presented evolutionary taxonomy to understand the interplay of diverse technology actors in a changing market environment. In fact, they claim that such "analyses will never fail to deliver a fascinating story", compare [SCHO07, p. 620]. Hence, the perspective of evolutionary theory of technical change will be applied to discuss the evolution of machine tool design paradigms.

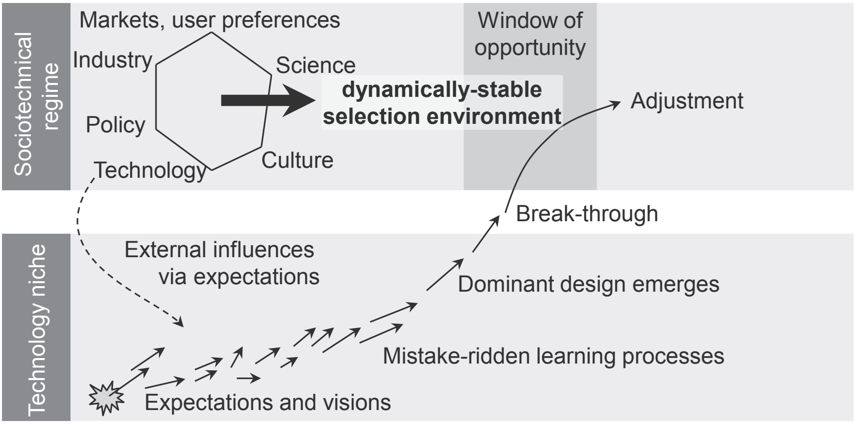
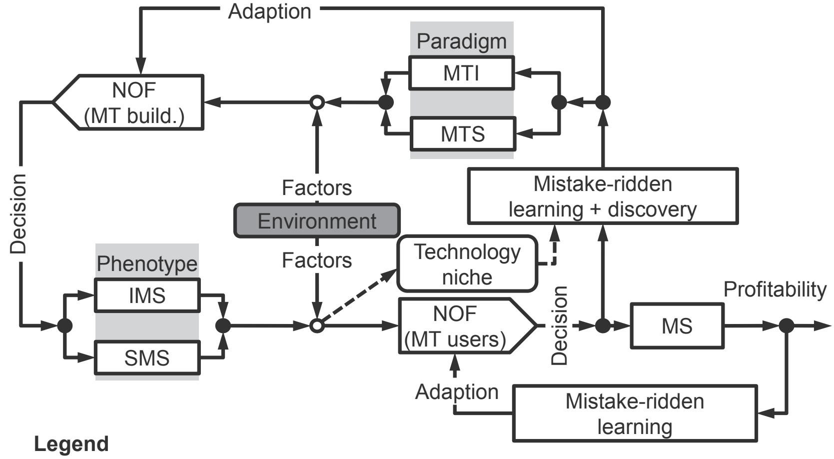


Figure 3.8: Dynamic multi-level perspective on technical transition [GEEL02]
Dynamische Mehrebenenperspektive auf technologische Übergänge

3.4 Interim conclusion - Heuristic frame of reference

Based on the review of evolutionary theory of technical change the heuristic frame of reference will be set up. This frame of reference will contain all relevant entities and their relations which drive the advance of the manufacturing technology integration paradigm, compare [KUBI77, p.18]. Figure 3.9 illustrates the development of the manufacturing technology integration paradigm between users, builders of machine tools, and the market environment as perceived by the author.



Legend

IMS	… Integrated manufacturing system	NOF	… Notion of fitness
SMS	… Segregated manufacturing system	MS	… Manufacturing system
MTI	… Manufacturing technology integration	MT	… Machine tools
MTS	… Manufacturing technology segregation	build.	… builders

Figure 3.9: Heuristic frame of reference

Heuristischer Bezugsrahmen

As can be seen, the structure of relations corresponds to Dosi's perception of a complex structure of feed-backs between machine tool builders and users under the influence of the external market environment, compare [DOSI97, p. 1536]. At the centre of the depicted model the market environment may be found which influences the users and builders of machine tools. Machine tool users are faced with multiple alternatives when deciding which manufacturing system to use, see figure 3.9: box "Phenotype". All these alternatives are physically available and not just abstract design concepts. Machine tool users decide which phenotypes to integrate into their manufacturing system. From these decision alternatives machine tools users choose machine tools that correspond to their current notion of fitness, see figure 3.9: arrow "NOF (MT users)". These machine tools are employed in the manufacturing system. The production system itself yields profitability which may or may not deviate from the forecasted profitability during the selection process. Through mistake ridden learning, machine tool users adapt their notion of fitness based on their gained experiences so as to improve their decision making process.

Machine tool builders themselves also adapt their notion of fitness through mistake-ridden learning based on the decisions made by machine tool users and based on technology niches set up to test multi-technology platforms. This discovery process has, for example, led to the idea of designing machine tools which integrate more than one manufacturing technology. Design alternatives and factors from the market environment lead to decision alternatives that are assessed according to the current notion of fitness of machine tool builders, see figure 3.9: box “Paradigm”. These decisions lead to the manufacturing of either single-technology machine tools or multi-technology platforms which again, in interaction with the factors from the market environment lead to decision alternatives for machine tool users. In contrast to the selection alternatives of machine tool users, the design alternatives are intellectual concepts and not physically available. These concepts represent the paradigmatic level of the technology paradigm. It can be concluded that the notion of fitness at both, the phenotypic and the paradigmatic level plays a critical role for the success of the manufacturing technology integration paradigm in a market environment.

Technology niches assume a somewhat unique role, because machine development takes place without the affirmation of the market environment. Technology niches are set up by machine tool builders or academic research based on expectations and believes. As long as the technology actors keep their expectation and believes the technology niche remains alive whether or not the market environment shares the respective notion of fitness.

Multi-technology platforms may be regarded as macro-inventions. Macro-inventions such as multi-technology platforms are only applied if they are justifiable within the notion of fitness created by machine tool users to evaluate the profitability of a new production technology a priori. However, the notion of fitness is created empirically by mistake-ridden learning from past experiences. As such the progress of the notion of fitness is slow. Hence, machine tool builders developing a macro-invention such as multi-technology platforms run at risk of inventing a technology which is not accepted by the market. This is in particular the case if the advantages of multi-technology platforms cannot be outlined by the notion of fitness of machine tool users.

It can be concluded, that the successful development and market application of multi-technology platforms and integrated manufacturing systems depends on the current notion of fitness of machine tools. Hence, the current notion of fitness of multi-technology platforms should be analysed as to whether it may serve to justify the application of integrated manufacturing systems.

3.5 Current notion of fitness of multi-technology platforms

The historical evolution of machine tool design and their economic justification have been reflected comprehensively by numerous authors from diverse backgrounds already, compare e.g. [WITT60; BRUI65; WECK06b, p. 4 et sqq.; WECK06a, p. 2 et sqq.; SPUR91; ROSE63; ARNO01; CARL84; FRAN86]. Neither the depth nor the width of historic research presented elsewhere will be reproduced here. This section solely intents to outline very selectively some of the past developments which might help identifying the origin and motivation of manufacturing technology integration. In this course, the current status of research with regard to economic justification of complex multi-technology platforms will be discussed.

Figure 3.10 depicts the classification scheme of manufacturing systems according to DIN 69651, compare [DIN85; WECK06b; HEIS90b; HEIS90a; REGE12, p. 15 et sqq.]. The scheme reflects DIN 8580 which classifies manufacturing technologies and thus bears the manufacturing technology segregation paradigm. Regel emphasizes that nowadays DIN 8580 may coin the classification of manufacturing systems only “superficially”, compare [REGE12, p. 15]. The trend towards manufacturing technology integration and increasing automation complicates the unambiguous classification of manufacturing systems consistently, compare [REGE12, p. 15]. Hence, machine tools for multiple processes (= multi-technology platforms) may appear as a *foreign body* within the taxonomy of DIN 69651. The difficulty to locate multi-technology platforms in existing classification schemes of manufacturing systems will be judged as a first indication that manufacturing technology integration represents indeed an independent machine tool design paradigm.

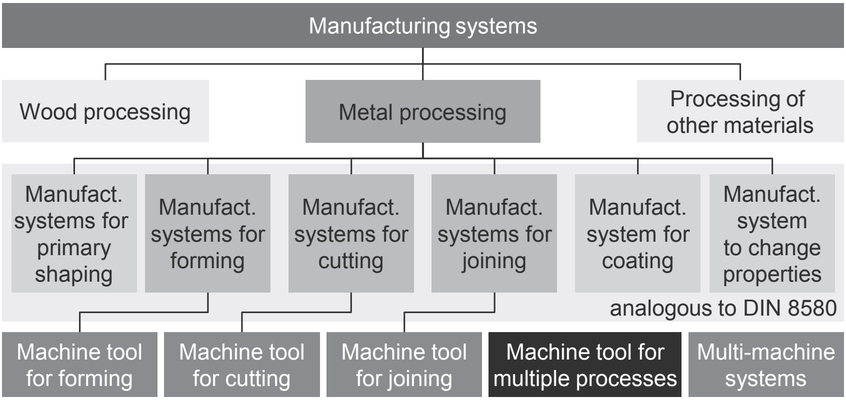


Figure 3.10: Classification of machine tools for metal processing according to DIN 69651
Einteilung von Werkzeugmaschinen für die Metallbearbeitung DIN 69651

Figure 3.11 shows an alternative scheme to classify machine tools which was introduced by Weck in 1988, compare [WECK88]. Instead of manufacturing technologies, Weck applies the degree of automation to discern five distinct classes of manufacturing systems. Conspicuously, the increasing degree of automation *raises the technological complexity* of manufacturing systems significantly. But, as outlined in section 3.3 Gutmann emphasizes that for the biological domain evolution may take place through both, increasing complexity or through *performance-enhancing simplification*, compare [GUTM89, p. 50]. Altschuller recognizes both pathways in technological evolution, too. In fact, he seems to prefer simplification to complication as he defines a key evolutionary principle of technology as being “from complexity to simplicity”, compare [ALTS86; ALTS98; BAES03, p. 179; HERB00; TERN98]. Hence, technology actors of the machine tool branch had to justify choosing the opposite pathway of ever increasing complexity through creation of a *justification pattern* within their notion of fitness of manufacturing systems that links increasing functional complexity to economic efficiency.

Of course, the macroeconomic view on global wage distribution discussed in figure 3.5 provides ex post a convincing rationale for automation and machine tool complexity in high-wage countries. However, some doubts should be nursed as to whether this macroeconomic justification pattern dominated the selection environment of the machine tool sector on a microeconomic level which obviously amplified automation for several decades.

At this point it should be noted that selection decisions for machine tools are naturally strongly influenced, if not solely taken by engineers. But during their academic training most engineers are only merely confronted with production, cost, and logistic theory which are mostly promoted by economic instead of engineering faculties. It may be hypothesized that most engineers applied the comparably simple “machine hour rate calculation” as outlined by VDI 3321, compare [VDI94; KLOC08, p. 374 et sqq.], to justify investment decisions besides the application of an economic efficiency calculation provided by machine tool builders. Hence, this mathematical calculation model must provide some indication for the benefits of automation and thus create a selection environment which makes machine tool builders increase the degree of automation through Lamarckian evolution.

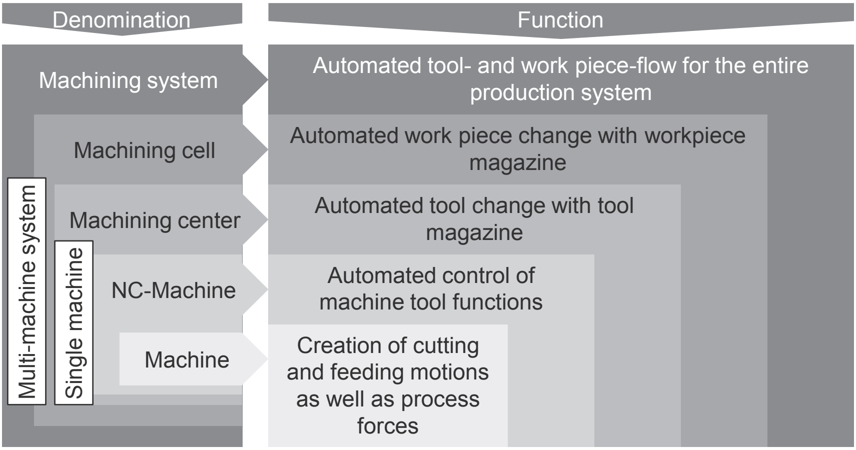


Figure 3.11: Denomination of manufacturing systems according to automation degree
Bezeichnung der Fertigungssysteme nach Automatisierungsgrad

Expression (3.1) depicts the machine hour rate calculation according to VDI 3321, compare [VDI94; KLOC08, p. 374 et sqq.]. Fixed costs for the machine and their operators are fully variabilized through the definition of the machine and labor hour rate K_{MH} and K_{LH}. Furthermore, the approach implicitly assumes full system utilization. [HAGE13]

$$K_F = \overbrace{(K_{MH} + K_{LH})}^{K_{ML}} \cdot \overbrace{(t_h + t_n)}^{t_e} \tag{3.1}$$

If compared to production and cost theory depicted e.g. by Fandel for the business administration domain, compare [FAND05], or logistic theory promoted by Nyhuis and Wiendahl, compare [NYHU09], it is evident that the calculation method clearly represents an oversimplification of the actual complexity of production environments. However, although the approach is rather straightforward, it provides a clear justification pattern for an increasing degree of automation, see left column in figure 3.12. A comparable and demonstrative pattern was presented by Saljé and may be found in [WECK06a].

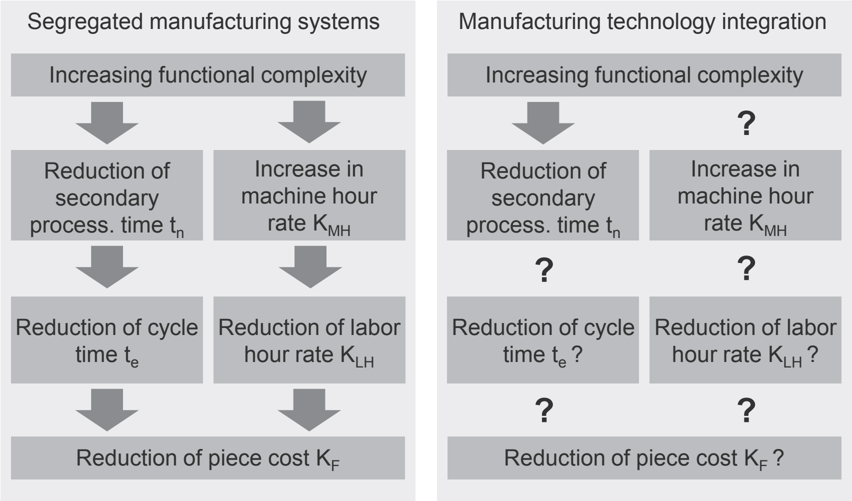


Figure 3.12: Justification pattern within notion of fitness to rationalize machine complexity

Begründungsstruktur zur Rationalisierung von Maschinenkomplexität

As long as the individual technologies remain segregated between machine tools the increasing degree of automation may possess two major effects. Firstly, it reduces the secondary processing time t_n and as a consequence the cycle time t_e due to the automation of auxiliary processing steps. Secondly, automation lowers the amount of human labor required and thus the labor hour rate K_{LH}. As long as the reduction of labor hour rate K_{LH} overcompensates the increase of machine hour rate K_{MH} due to increasing technological complexity, the joint machine and labor hour rate K_{ML} decreases as well. In summary, this justification pattern provides a convincing rationale to link increasing functional complexity to a reduction of piece costs K_F.

It should be noticed that the pattern may actually be applied to all manufacturing systems depicted in figure 3.11. In fact, technology actor learned for decades that an increasing degree of functional complexity due to automation may be associated with smaller secondary processing times t_n and smaller secondary processing times in turn with smaller piece costs K_F. As a consequence, increasing functional complexity and decreasing secondary processing times are largely treated as quasi-efficiency criteria by technology actors of the machine tool sector. This hypothesis may be confirmed by studying some titles of the popular magazine “MaschinenMarkt” which is broadly read by German engineers. Three exemplary titles will be depicted here:

- “Attachment axis with six spindles makes machining center hum” [KÖNI13]
- “Vertical turning machine reduces secondary processing times in shaft machining” [HAGE13]
- “Emag promises workpiece change in one second” [KUTT10b]

The steadiness of the economic justification pattern facilitated the absorption and amplification of automated machine tools by the market (selection) environment, since technology actors could constantly apply similar quasi-efficiency criteria to rationalize investment decisions. Hence, without neglecting the great technological difficulties that had to be overcome in the course of manufacturing system automation all inventions that aimed at matching the economic justification pattern depicted in the left column of figure 3.12 must be considered as being “micro inventions” in terms of the evolutionary theory of technical change outlined in section 3.3.

At first sight, manufacturing technology integration may appear as a consequent advancement of existing trends with regard to the functional enhancement of machine tools but actually it is not. The reason being that manufacturing technology integration may impact the layout of production systems much more profoundly than conventional automation, compare [KORE98]. As a consequence, the justification pattern discussed above is hardly suitable to rationalize manufacturing technology integration as will be demonstrated in the following.

Manufacturing technology integration aims at substituting an existing system of at least two single-technology machine tools by multi-technology platforms, compare [JALI09]. Thus, all processes that were carried out by more than one sequenced single-technology machine tool have to take place on a single multi-technology platform if the manufacturing system is “integrated”. Hence, even if secondary processing times are reduced through technology integration the greater number of machining processes may increase cycle times t_e compared to the cycle time of the bottleneck machine within the segregated manufacturing system, compare [JALI09, p. 13]. The relation between the reduction of secondary processing time through manufacturing technology integration and cycle times is not obvious, see right column of figure 3.12.

Due to the likelihood of greater cycle times multi-technology platforms have to be paralleled to achieve the same productivity as sequenced single-technology machine tools, see [KORE98, p. 371] for similar argument. According to Koren et al. parallelization of machine tools may imply negative effects on part quality because statistical “mixing” of parts from two machines can increase the overall variation, compare [KORE98, p. 370]. If the argumentation is reversed and a single unparalleled multi-technology platform is assumed to substitute a segregated manufacturing system the cycle times of the integrated manufacturing system have to be reduced by a factor significantly greater than one although more processes are to be carried out on the multi-technology platform, compare [KLOC11, p. 296 et sqq.].

The number of multi-technology platforms required depends on the desired output quantities. However, the output quantities are neglected within the machine hour calculation approach. No clear relation prevails between the increasing functional complexity aiming at manufacturing technology integration and the machine and labor hour rate. Thus, the machine hour rate calculation is an inadequate approach to rationalize manufacturing technology integration. Furthermore, due to the greater cycle times t_e the degree of system utilization increases and thus the likelihood of queuing in front of multi-technology platforms increases compared to segregated machine tools, compare [JALI09, p.13].

Manufacturing technology integration may seem advantageous in terms of the quasi-efficiency criteria increasing functional complexity and decreasing secondary processing times. However, the conventional pattern to rationalize increasing complexity in the course of automation, see left column figure 3.12, is unsuitable for economic justification of functional enhancement of machine tools aiming at manufacturing technology integration. In fact, later chapters of this thesis will apply more sophisticated models put forward mostly by Gutenberg, Fandel, and Wiendahl to elucidate the question under which circumstances manufacturing technology integration is economically justified, see [GUTE83; FAND05; NYHU09].

An “ideal” selection environment with perfect knowledge would adjust the economic justification pattern, too. However, selection decisions are taken by humans who tend to repeatedly apply a once-learned scheme. Furthermore, causal chains are not fully thought through. If the first elements of the known justification pattern, so-called quasi-efficiency criteria, are recognized the subsequent logic is assumed to be on hand without giving it a second thought. Under such circumstances it is no wonder that technology actors, in particular machine tool builders who have a monetary interest in machine tool complexity, attempt to promote integrated manufacturing systems by referring to quasi-efficiency criteria, increasing complexity and reduction of secondary processing times. Again, some titles of “MaschinenMarkt” shall serve as proofs of this hypothesis:

- “Additional manufacturing technologies increase productivity in ultraprecision machining” [KUTT07a]
- “Complete machining in a single machine tool decreases processing times” [KUTT07b]
- “Complete machining reduces throughput time for lot size 1, too” [FEIN11]

On the academic side the discussion of manufacturing technology integration mostly focusses on the derivation of a “dominant design” of multi-technology platforms, see figure 3.8. As outlined in section 3.2 it takes place in research communities concerned with the design and operation of machine tools, compare [MORI08], as well as research communities focusing on the study of manufacturing processes, compare [BYRN03, p. 497].

Compared to the technological discussion the economic justification of increasing machine tool complexity is not disregarded but clearly assumes a second rank. Byrne et al. emphasize the temporal effects of manufacturing technology integration, compare [BYRN03, p. 497] citing [GRUN02], through reduction of non-value adding processing times, compare [FEIN05; WEIN01], a reduction of inventory, compare [GRUN02], a reduction of floorspace and logistic expenditures, as well as positive effects on accuracy due to the elimination of re-clamping operations, compare [POGA00; CHOU00].

Denkena and Müller in 2005 present a model to justify manufacturing technology integration, compare [MASC05, p. 87]. According to the model the manufacturing cost K of a workpiece comprises the prime manufacturing cost K_{FE}, the order repetition cost K_{AW}, the preparation cost K_{VO}, and the consequential cost K_{FO}. The symbol m represents the lot size and o the number of orders. The cost fractions are added for all $L_{serial,SMS}$ machine tools of the segregated manufacturing system.

$$K = \sum_{l=1}^{L_{serial,SMS}} K_{FE} + \sum_{l=1}^{L_{serial,SMS}} \frac{K_{AW}}{m} + \sum_{l=1}^{L_{serial,SMS}} \frac{K_{VO}}{o \cdot m} + \sum_{l=1}^{L_{serial,SMS}} K_{FO} \tag{3.2}$$

Based on the mathematical expression, Denkena and Müller argue that the major advantage of manufacturing technology integration is the reduction of workforce because only one instead of two or more serial machines has to be operated. However, they do not mention the risk of greater cycle times and the likelihood to parallel multi-technology platforms in order to achieve the same output than segregated manufacturing systems. Thus, the approach neglects the parallel configuration that the integrated manufacturing system may assume.

Brecher et al. emphasize the advantages of manufacturing technology integration as it may enable machining in a single clamping which would reduce cycle time, compare [BREC08; BREC12b, p. 596 et sqq.]. Brecher recognizes that individual technology resources are utilized sequentially in single workspace multi-technology platforms and remain idle while other resources are applied to machine the workpiece, compare [BREC12a]. To increase the average degree of resource utilization of technology resources and thus the output, Brecher suggests equipping multi-technology platforms with a second workspace and allowing for the traveling of technology resource between the workspaces, compare [BREC08; BREC12b, p. 596; BREC12a; BREC13].

Moriwaki dedicated the last section of the 2008 CIRP keynote paper entitled “Multi-functional machine tools” to “Economical justification” citing a single paper, compare [MORI08, p. 747]. The respective paper illustrates research conducted by a collaboration of Japanese machine tool builders and universities, compare [NAKA07]. The author Nakaminami analyses the economic efficiency of multi-axis turning machines and focusses thus on double workspace multi-technology platforms for sequential machining, see figure 3.3. Nakaminami calculates the required cycle time reduction such that conventional turning machines yield the same profit than multi-axis turning machines. The profit π is given by the difference of value creation V and cost C.

$$\pi = V - C \tag{3.3}$$

The value creation V is the product of value creation per workpiece v and number of machined parts y.

$$V = v \cdot y \tag{3.4}$$

The cost C are the sum of cost per machine tool c_{MT} and direct cost per workpiece c_d:

$$C = c_{MT} + c_d \cdot y \tag{3.5}$$

The number of workpieces y machinable during the reference period T may be calculated by the following expression, where t_{cyc} is the cycle time per workpiece:

$$y = \frac{T}{t_{cyc}} \tag{3.6}$$

Nakaminami equalizes the profit of a conventional turning machine π_c and the profit of a multi-axis turning machine π_m. The index “c” denominates the conventional turning machine whereas the index “m” stands for the multi-axis turning machine.

$$\pi_c = \pi_m \tag{3.7}$$

Applying expression (3.3) - (3.6) to expression (3.7) the required cycle time $t_{cyc,m}$ of the multi-axis turning machine may be determined as follows:

$$t_{cyc,m} = \frac{t_{cyc,c}}{1 + \frac{t_{cyc,c} \cdot \left(c_{mt,m} - c_{mt,c}\right)}{v \cdot T}} \tag{3.8}$$

Based on this efficiency model the authors conclude the necessity to reduce cycle times by a factor of 1.15 to 1.5 to justify multi-axis turning machines economically, compare [NAKA07, p. 85] referring to [MURA03]. A similar approach based on the equalization of profit was presented by Tönissen in 2012 taking into consideration workpiece complexity as well, compare [TÖNI12]. However, both publications neglect that at equal profit the diverse machine tools yield distinct output in terms of machined workpieces per reference period. Hence, the comparisons do not take place under similar boundary conditions which reduces the validity of the results. Furthermore, Nakaminamis calculation approach focusses on the substitution of conventional turning machines by multi-axes turning machines and is not applicable to integrated manufacturing systems in general as it does not consider the configuration of the manufacturing systems.

4 Problem

The advancement of machine tool and manufacturing system design paradigms is an evolutionary process. The selection mechanism of machine tool designs comprises the application of a notion of fitness which is created by technology actors based on past experiences. Macro-inventions such as multi-technology platforms differ significantly from established production resources. Since technology actors have no experiences with multi-technology platforms they currently need to revert to known concepts to evaluate the propitiousness of manufacturing technology integration.

In the recent decades technology actors applied the machine hour rate calculation to justify the continually increasing functional complexity of machine tools. The recent section has shown that conventional automation such as tool exchange units or workpiece exchange units are justifiable by the machine hour rate calculation.

Multi-technology platforms will only be selected by technology actors if this production technology is justifiable by the notion of fitness i.e. the machine hour rate calculation. However, the notion of fitness must be capable of adequately mapping the consequences of manufacturing technology integration with regard to the configuration of the manufacturing system and output quantities to be produced which may differ significantly between an integrated and a segregated manufacturing system.

The configuration of the manufacturing system and the output quantities to be produced are not reflected by the machine hour rate calculation. Thus, it is impossible to rationalize increasing machine tool complexity that aims at manufacturing technology integration through the machine hour rate calculation. It may be concluded that a notion of fitness based on the machine hour rate calculation is inappropriate to fully map the consequences of manufacturing technology integration. Consequently, application of the machine hour rate calculation leads to biased decisions in the scope of manufacturing technology integration.

Academic research is aware of the difficulty to rationalize machine tool complexity that aims at manufacturing technology integration by means of the machine hour rate calculation. Diverse mathematical approaches have been applied in the past with regard to cost but none of the approaches accounts for the configuration change of the manufacturing system that may occur. Furthermore, no attention has been drawn to the modeling of throughput times. It can be concluded that so far no holistic deductive theory of economic efficiency of manufacturing technology integration has been defined.

5 Research objective and research approach

5.1 Research objective

The *research objective* of this doctoral thesis is to determine the *conditions of economic efficiency of integrated manufacturing systems* in comparison to segregated manufacturing systems by quantitative models based on production, cost, and queuing theory. In other words, the thesis elucidates the fitness of the machine tool and manufacturing system design paradigm “manufacturing technology integration” under various production environments and for diverse integrated manufacturing systems. The efficiency conditions will be applied to discuss their implications with regard to the efficient design of multi-technology platforms.

The research objective addresses the currently prevailing *knowledge deficit* about economic efficiency attributed to manufacturing technology integration, which may distort decision making with respect to integrated manufacturing systems systematically. Enhanced knowledge about the economic efficiency of manufacturing technology integration may improve and facilitate e.g. the layout of production facilities on the hand of production planers or guide the design process on the hand of machine tool builders.

5.2 Research approach

Ulrich and Hill distinguish three research approaches of distinct nature to address knowledge deficits within applied sciences [ULRI76b, p. 308]:

- The factor-theoretical approach according to Erich Gutenberg [GUTE83]
- The system-theoretical approach according to Hans Ulrich [ULRI68]
- The decision-theoretical approach according to Edmund Heinen [HEIN68]

The factor-theoretical approach closely follows the methodological paradigms of natural sciences which are dominated by Popper’s hypothetico-deductionism. In its core Gutenberg envisions business administration to be a nomothetic science which means that it should formulate laws according to physics or chemistry.

As distinct from Gutenberg, Ulrich and Heinen emphasise the formative function of business administration, but both embark on different paths to meet their claim. The system-theoretical approach according to Ulrich is multidisciplinary and enables in particular the integration of human behavioural patterns. However, due to its broadness the approach may lack precision and problem-solving power.

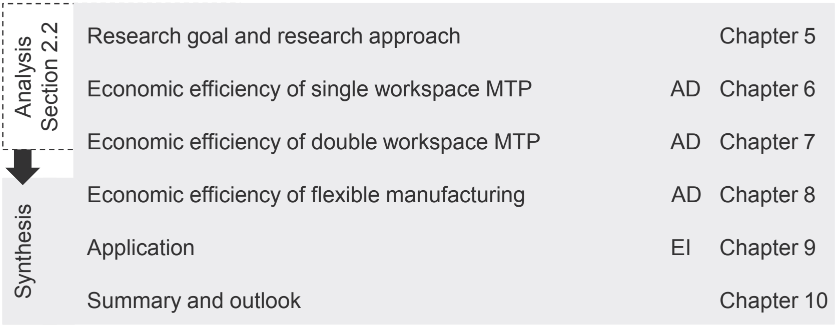
The decision-theoretical approach establishes theoretical explanatory and design models for pragmatic purposes. Although the approach may incorporate human behaviour, it is mostly based on quantitative models also present within the factor-theoretical approach. [ULRI76b]

This thesis pursues the decision-theoretical approach due to its “strong integration of explanatory and design functions“ [ULRI76b]. As outlined the decision-theoretical approach involves the application of quantitative models to model the consequences of the decision alternatives "manufacturing technology integration" and "manufacturing technology segregation".

Hence, quantitative models are required to derive the conditions of economic efficiency of single workspace multi-technology platforms (chapter 6, see figure 5.1), double workspace multi-technology platforms (chapter 7), as well as evaluate the propitiousness of a flexible manufacturing strategy in comparison to a conventional manufacturing strategy (chapter 8). The decision-theoretical approach is implemented through three hypotheses about the nature of the quantitative models to be applied in the chapters 6-8:

1. The conditions of economic efficiency of single workspace multi-technology platforms may be predicted based on production, cost, and queuing theory (chapter 6).
2. The conditions of economic efficiency of double workspace multi-technology platforms may be predicted based on discrete-event simulation models (chapter 7).
3. The conditions of economic efficiency of flexible manufacturing may be predicted based on a probabilistic decision model (chapter 8).

In chapter 9 the quantitative models introduced will be applied to discuss two case studies of manufacturing technology integration. Chapter 10 concludes the thesis with a summary and an outlook.



Outline: EI: Empirically-inductive/ AD: Analytically-deductive
MTP: Multi-technology platform

Figure 5.1: Modus operandi of synthetic part of thesis

Vorgehensweise im synthetischen Teil der Dissertation

6 Economic efficiency of single workspace MTP

The objective of this chapter is to derive the conditions of economic efficiency of integrated manufacturing systems consisting of multi-technology platforms with a single workspace in comparison to segregated manufacturing systems consisting of single-technology machine tools. Three separate efficiency criteria are considered: productivity, profitability, and throughput time.

Figure 6.1 shows the technology chain of a segregated and an integrated manufacturing system. The technology chain consists of multiple manufacturing technologies which are applied to convert the raw material into the final product. In case of segregated manufacturing the manufacturing technologies remain segregated between the machine tools. This signifies that an individual machine tool is applied to execute each manufacturing technology. In case of manufacturing technology integration multi-technology platforms are introduced into the technology chain to carry out at least two of the manufacturing technologies of the technology chain. This thesis focusses on the comparison of the segment of the technology chain that is integrated to the corresponding segment of the segregated manufacturing system. The remaining segments of the technology chain are assumed to be similar for each of the two manufacturing alternatives and will be neglected in the efficiency comparison.

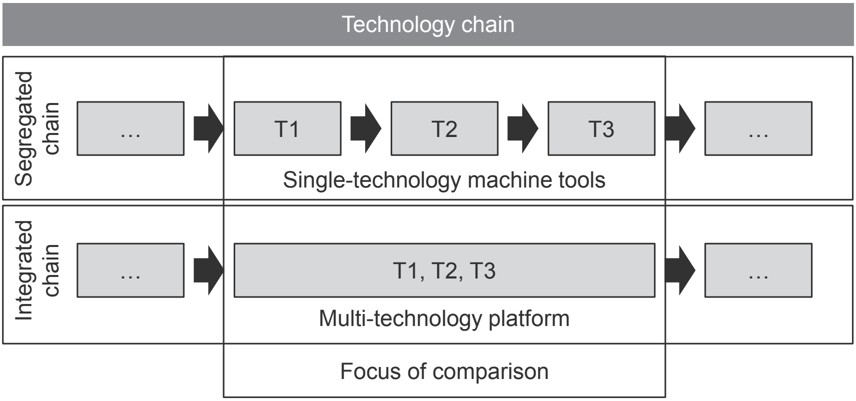


Figure 6.1: Focus of comparison of integrated and segregated manufacturing systems
Fokus des Vergleichs integrierter und segregierter Fertigungssysteme

The efficiency of a manufacturing system with regard to productivity, profitability, and throughput time depends on the conditions under which it is operated. Within the scope of this thesis no real manufacturing systems are studied. The conditions of economic efficiency of integrated manufacturing systems are derived based on mathematical models of the manufacturing systems. These models are part of a special production theory.

According to Dyckhoff a special production theory describes a specific statement system within general production theory, which is determined by

- the research objective,
- the extent of application and the implementation by the models of the structural core, and
- the method of resolution. [DYCK03, p. 713]

While the research objective was already specified above, the extent of application will be discussed in section 6.1. Furthermore, the *descriptive models* of segregated and integrated manufacturing systems are implemented mathematically by the static-deterministic equations of classical production, cost, and queuing theory within section 6.1. This modelling approach is chosen because it offers the possibility to deductively derive conditions of economic efficiency of manufacturing technology integration by means of algebraic transformations (method of resolution), see section 6.2. Based on the efficiency conditions three distinct synergy effects of manufacturing technology integration are discerned, see section 6.3, and implications for the design of single workspace multi-technology platforms are discussed, see section 6.4. Section 6.5 concludes with a short résumé about economic efficiency of manufacturing technology integration with single workspace multi-technology platforms.

6.1 Extent of application and model implementation

A special production theory of manufacturing technology integration comprises input-output relations of integrated and segregated manufacturing systems. The mathematical expressions which describe such input-output relations are called production functions. The implementation of production functions takes place in section 6.1.1.

However, the fitness of a manufacturing system is usually not evaluated based on input-output relations but on production costs. Therefore, production theory needs to be linked to a cost theory, compare [FAND05, p.258]. Apart from costs, Dyckhoff suggests considering further fitness criteria like the value creation of a production system which is not captured by cost functions and logistic properties like throughput times. In his view, production revenues and production costs should be represented within a profitability theory (“Erfolgstheorie”) [DYCK03, p. 716]. Corresponding profitability functions will be introduced in section 6.1.2. Section 6.1.3 discusses a throughput time function based on mathematical queuing theory.

Figure 6.2 distinguishes two basic domains of economic efficiency of manufacturing technology integration. The set of all supposable workpieces contains two subsets. Each subset comprises the workpieces that are either machinable by the integrated or by the segregated manufacturing system. Furthermore, the subset of workpieces, that are machinable by the integrated manufacturing system, may be subdivided into two domains. Within the first domain the integrated manufacturing system is the only production alternative that meets the quality requirements, see figure 6.2. This domain will be called the domain of *market niche development*, compare [SCHO07, p. 618]. Here, the machining of workpieces is economically efficient, if the value of output exceeds the production costs (absolute profitability).

In the second domain it is technically feasible to select either the integrated or the segregated manufacturing system. The primary focus of this thesis will be put on this domain. It will be referred to as the domain of *broad market application*, since “integrated manufacturing systems” may break through suddenly on existing markets currently covered by segregated manufacturing systems consisting of single-technology machine tools. This may happen as soon as the technology *and* the selection environment for integrated manufacturing systems has matured and previous believes are overthrown by the technology actors, compare [SCHO07, p. 617].

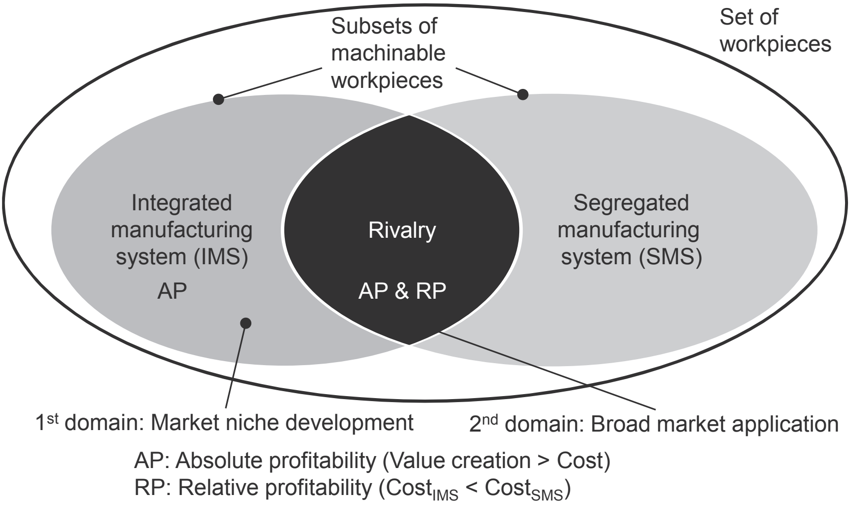


Figure 6.2: Domain distinction for manufacturing technology integration
Fallunterscheidung für Fertigungstechnologieintegration

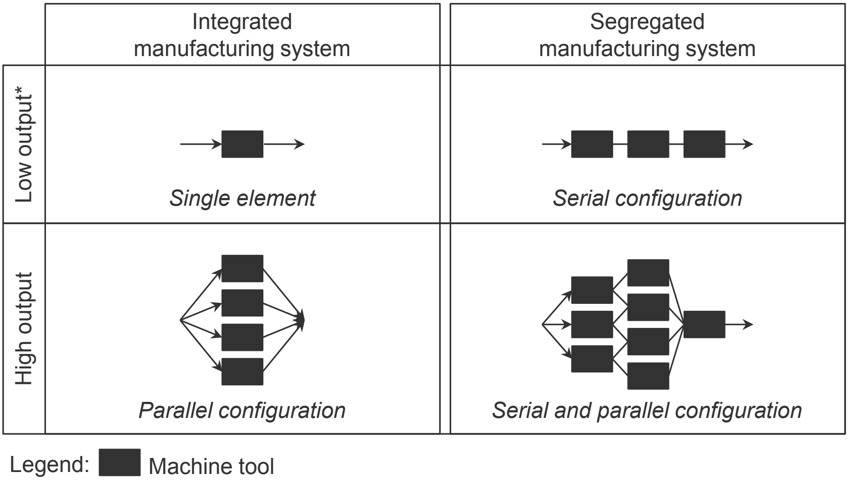
Apart from absolute profitability (AP) the relative profitability (RP) in comparison to the segregated manufacturing system becomes a condition for the efficiency of manufacturing technology integration within the intersection set, which is denominated by “rivalry” in figure 6.2. For the same type of orders and production volumes manufacturing systems designed according to alternative paradigms may yield distinct profitability and throughput times. The integrated manufacturing system is advantageous, if its profitability is higher than the profitability of the segregated manufacturing system, preferably at smaller throughput times.

6.1.1 Production function

A production function is a model of a manufacturing system, which describes the transformation from input to output [FAND05, p. 11]. The mathematical description of the input-output transformation must be capable of reflecting all configurations that a manufacturing system may assume. Hence, before introducing a mathematical model of the production function it should be clarified, which configurations may occur for the manufacturing systems under study.

The configuration of an integrated manufacturing system consisting of multi-technology platforms differs from a segregated manufacturing system consisting of single-technology stand-alone machine tools. This difference attributes to e.g. distinct system capacities, process times, or changeover times. Furthermore, due to the larger number of processes carried out on a multi-technology platform, more than a single multi-technology platform may be required to obtain the same productivity than the respective segregated manufacturing system.

As mentioned in section 3.4, this results in a parallel configuration of the integrated manufacturing system in oppose to a serial configuration of the segregated manufacturing system, compare [KORE98, p. 369] and see figure 6.3. However, depending on the desired output quantities it may be necessary to parallel single-technology stand-alone machine tools within the segregated manufacturing system, too. Hence, at high output quantities the segregated manufacturing system assumes a serial and parallel configuration which reflects the workload distribution between the sequential workpiece transformation steps.



**Minimum configuration suffices to produce output quantity.*

Figure 6.3: Possible system configurations of either manufacturing system
Mögliche Systemkonfigurationen beider Fertigungssysteme

General production theory distinguishes multiple types of production functions. Hence, the considered type should be specified. In the following the framework of the so-called Gutenberg-production function will be applied to describe integrated and segregated manufacturing systems mathematically. The Gutenberg-production function was introduced in 1951 by Erich Gutenberg [GUTE83, p. 221 et sqq.]. At time, this production function represented a paradigm shift within production theory due to its classification of production resources into potential and consumption factors [FAND05, p. 101].

Potential factors represent all elements like machine tools and their operators, which provide the capacity for the stepwise transformation of raw material into the final product. The technological properties of the manufacturing system determine the amount of consumption factors, mostly raw material and supplies, required for the considered transformation [FAND05, p. 101]. Due to the emphasis of technological properties the Gutenberg-production function is particularly suitable for the comparison of the technologically distinct integrated and segregated manufacturing systems. In the following the framework of the Gutenberg production function will be applied to adapt its mathematical equations for the comparison of integrated and segregated manufacturing systems.

Potential function

Within the scope of this thesis, potential functions describe the usage of machine tools. Based on the description of single machine tools the usage of the entire integrated and segregated manufacturing system will be derived deductively.

According to Gutenberg, a potential function describes the relation between the output x, the intensity of usage i_u, and the total operation time $T_{op,WS}$ of a work station during the reference period T [FAND05, p. 108]. The intensity of usage i_u refers to the productivity of the manufacturing processes. However, a variation of the intensity of usage is not considered in the following. It is assumed at this point that the same manufacturing processes are carried out on the multi-technology platform and the single-technology machine tools of the segregated manufacturing system and no variation of intensity takes place.

The following paragraphs discuss the maximum operation time $T_{op,WS,max}$ of a work station during a reference period T based on the available capacity $T_{av,WS}$. According to Nyhuis and Wiendahl the available capacity of a work station $T_{av,WS}$ depends on the minimum of either the available capacity of the machine tool $T_{av,MT}$ or the effective capacity of the operator $T_{ef,OP}$. [NYHU09, p. 64].

The available capacity of a machine tool $T_{av,MT}$ is smaller than the reference period T due to disruptions during operation like machine failures [NYHU09, p. 20]. The availability of a machine tool a_{MT} links the length of the reference period T to the available capacity of the machine tool $T_{av,MT}$. The availability a_{MT} itself depends on the failure probability of the machine tool p_{MT} [KLOC11, p. 296]:

$$T_{av,MT} = a_{MT} \cdot T = (1 - p_{MT}) \cdot T \tag{6.1}$$

Likewise, the available capacity of the operator $T_{av,OP}$ is smaller than the duration of the reference period T e.g. due to illnesses. The effective operator capacity may exceed the arithmetical available capacity $T_{av,OP}$, because operators may work overtime or take holiday shifts [NYHU09, p. 20]. In the following it is assumed that the available capacity of a work station $T_{av,WS}$ is always limited by the available capacity of the respective machine tool $T_{av,MT}$, because machine tools are in the focus of analysis.

Hence, the work station will machine orders whenever the machine tool is available. The operator will not be the limiting factor.

Unlike Gutenberg, who assumed a production system that produces a single type of workpiece, compare [GUTE83, p. 249 et sqq.], the following considerations refer to a variant rich workpiece spectrum. Such a variant rich workpiece spectrum stipulates the adaption of the work station to each workpiece type. This adaption is called the "changeover" of the machine tool [WIEN07, p. 786]. During changeover of the machine tool no parts are produced. In order to reduce this unproductive time workpieces are produced in lots, in particular at early stages of the value stream. Lot production leads to a reduction of changeover time per part, because this time is attributed to the whole lot and not to a single workpiece.

The lots pass through the value stream from work station to work station and each step contributes to completion of workpieces. From the point of view of a work station a lot represents an order. Throughput elements describe all throughput time components of an order between two work stations [NYHU09, p.22], see figure 6.4. The throughput time $t_{tp,l}$ of the l-th stage of the transformation process consists of the interoperation $t_{io,l}$ and the operation time $t_{op,l}$. The operation time $t_{op,l}$ comprises times of processes that occupy the work station like changeover and machining, while the interoperation time $t_{io,l}$ describes the duration of processes which take place before the work station, e.g. transportation or waiting.

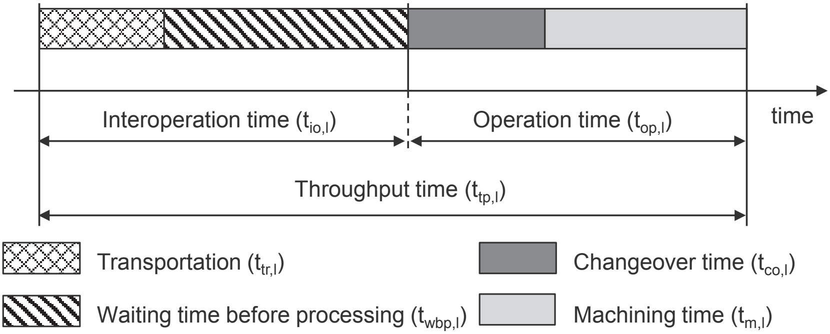


Figure 6.4: Throughput element
Durchlaufelement

Order arrival at a particular work station depends on multiple factors upstream of the value chain. The M/M/c queuing model, which will be applied as a reference to discuss the link between available capacity of a work station $T_{av,WS}$ and the maximum operation time $T_{op,max}$ during the reference period T, considers order arrival following a so-called discrete-time Markov Process with exponentially distributed interarrival times [GROS08, 219].

At the instance of order arrival, the work station may either be occupied with a previous order or start processing of the new order immediately. In case of occupation the new order queues in front of the work station and waits before being processed until all previous orders are completed (FIFO-principle). According to the M/M/c queuing model the mean length of the queues depend on the mean utilization U_m of the available capacity $T_{av,WS}$ during the reference period T.

If the mean utilization U_m of a work station is larger than 80 % of the available capacity $T_{av,WS}$ the mean waiting time before processing t_{wbp} exceeds the mean operation time t_{op} of an order by a factor of about three, compare [NYHU09, p. 45]. These high waiting times are usually avoided, because they affect the lead time negatively. To achieve this, the maximum operation time $\widehat{T}_{op}$ during the reference period T will be limited to a maximum mean utilization $U_{m,max}$ = 80 % of the available capacity of the work station, compare [GROS08, p. 73]. The following expression summarizes the relation between reference period T and the maximum operation time of a work station $\widehat{T}_{op,MT}$:

$$\widehat{T}_{op,MT} = a_{MT} \cdot U_{m,max} \cdot T \tag{6.2}$$

The last paragraphs emphasized the critical role of operation time t_{op}, which delimits the number of orders o processable by the work station during the reference period T. In the following, a model of operation time t_{op} will be set up that may comprise multiple time components at distinct degrees of detail. To avoid excess complexity the operation time model needs to emphasize quantities, which are of interest to the comparison of integrated and segregated manufacturing systems.

According to the scientific discourse integrated manufacturing systems are viewed to be particularly suitable for production of small lot sizes and complex geometries, since secondary processing times and changeover times are reduced through manufacturing technology integration, compare [MORI08, p. 736/ p. 747]. To evaluate this hypothesis by the static-deterministic production theory the lot size and the number of features must be explicitly included into the operation time model.

Workpieces consist of a variety of geometric elements, which are e.g. of a cylindrical, a plane, or a freeform shape. Such geometric elements are called features. Workpiece complexity will be quantified in the following by the number of workpiece features n. Furthermore, it is assumed that the machining time of a workpiece grows proportionally over the number of features n i.e. the processing time t_p per feature is constant.

Before machining the workpiece is placed into the machine tool and will be retracted from the workspace after completion of the machining process. The duration of placement and retraction is quantified by the workpiece change time t_{wc}. Hence, the total machining time t_m of the m workpieces of the lot is determined by the following equation:

$$t_m = m \cdot \left(t_{wc} + n \cdot t_p\right) \tag{6.3}$$

The total operation time t_{op} of a lot is the sum of changeover time t_{co} and machining time t_m:

$$t_{op} = t_{co} + t_m = t_{co} + m \cdot \left(t_{wc} + n \cdot t_p\right) \tag{6.4}$$

This model of operation time created by the author emphasizes workpiece complexity and deviates from the conventional classification of operation time components established by the Association of German Engineers, compare [VDI94, p. 5]. The time components of the operation time model t_{co}, t_{wc}, and t_p will now be linked to the model of VDI 3321 to outline their definitions.

VDI 3321 distinguishes primary processing time t_h and secondary processing time t_n as well as additional time t_v and personal recovery time t_{er}. These time components make up the basic time t_g per *workpiece*. Primary processing time t_h consists of the idle time during jogging the axis t_{jog} and the time of tool engagement t_c. During tool engagement the manufacturing process mechanisms interact with the workpiece to change its geometry or its properties. Secondary processing time t_n comprises proportional tool exchange time t_t, proportional changeover time of the machine tool t_{co}, and the workpiece change time t_{wc}. The additional time t_v describes irregular disruptions of the production process, e.g. due to machine failure, whereas the personal recovery time refers to the duration of the operator's breaks. [VDI94; KLOC08, p. 375 et seq.]

Figure 6.5 links the time components of the basic time t_g from VDI 3321 to the operation time model. The processing time t_p *per feature* consists of jogging time t_{jog}, the actual time of tool engagement t_c, and the proportional tool exchange time t_t. In contrast to the basic time model the operation time model does not relate the tool exchange time to the number of workpieces machinable during tool life, instead the number of features per workpiece machined with a single tool. The machine changeover time t_{co} and the workpiece change time t_{wc} are incorporated in both models. The additional time t_v related to machine failure was already incorporated in the model for the available capacity of the machine tool $T_{av,MT}$. Personal recovery time t_{er} is part of the model for effective operator capacity. However, it was assumed that the effective operator capacity is neglected, since machine tools are in the centre of attention.

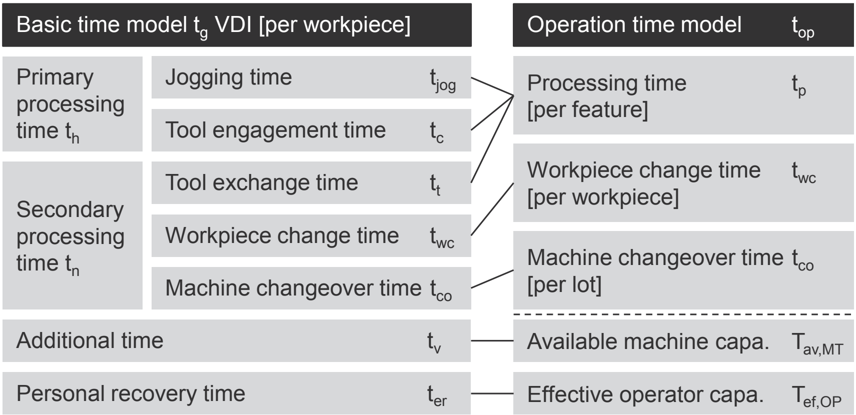


Figure 6.5: Comparison of basic time model according to VDI and operation time model
Vergleich des Basiszeitmodells nach VDI und des Operationszeitmodells

The total operation time T_{op} during the reference period T is equal to the number of orders o multiplied by the operation time per order t_{op}:

$$T_{op,MT} = o \cdot t_{op,MT} = o \cdot \left[t_{co,MT} + m \cdot \left(t_{wc,MT} + n \cdot t_{p,MT}\right)\right] \tag{6.5}$$

The total operation time T_{op} must be smaller or equal to the maximum operation time $\hat{T}_{op,MT}$ of the machine tool during the reference period T.

$$T_{op,MT} \leq \hat{T}_{op,MT} = a_{MT} \cdot U_{m,max} \cdot T \tag{6.6}$$

The maximum number of orders $o_{crit,MT,l}$ machinable by a machine tool at the l-th stage of the transformation process is determined by the following equation:

$$o_{crit,MT,l} = \text{floor}\left[\frac{\hat{T}_{op,MT}}{t_{op,MT}}\right] = \text{floor}\left[\frac{\hat{T}_{op,MT}}{t_{co,MT} + m \cdot \left(t_{wc,MT} + n \cdot f_l \cdot t_{p,MT}\right)}\right] \tag{6.7}$$

The expression embraces the workload fraction f_l which describes the relative amount of features machined at the l-stage of the transformation process. In case of manufacturing technology integration, all n features are machined on the multi-technology platform, therefore f_{IMS} is equal to one. The number of orders o processable by the segregated manufacturing systems depends on the workload of the bottleneck machine which carries the workload f_{max}.

If the number of orders o exceeds the maximum number of orders $o_{IMS,max}$, more than a single machine tool is required to achieve the desired productivity. The number of paralleled machine tool $L_{para,MT}$ may be calculated by the following expression:

$$L_{para,l} = \text{ceil}\left[\frac{o}{o_{crit,MT,l}}\right] \tag{6.8}$$

Consumption function

In the last section, the usage of potential factors, in particular of machine tools, was described mathematically by potential functions. Apart from the potential factors the transformation of input to output requires consumption factors. Such consumables of the transformation process are e.g. raw materials, supplies, wear parts, and electrical energy. [FAND05]

The amount of consumables needed to manufacture a particular amount of output is represented mathematically by consumption functions. The output quantity x is determined by the number of orders o and the number of workpieces per lot m. Furthermore, due to the necessity to emphasize workpiece complexity in the comparison of integrated manufacturing systems to segregated manufacturing systems it is assumed that the amount of consumables required per workpiece depends on the number of features n. Hence, the output quantity x represents the number of features machined during the reference period T.

$$x = o \cdot m \cdot n \tag{6.9}$$

The Gutenberg-production function distinguishes a direct and an indirect relation between consumable γ and the output quantity x. A direct relation is characterized by a constant, direct production coefficient $a_{\gamma,d,MT}$ between the consumable and the output quantity. The multiplication of the production coefficient $a_{\gamma,d,MT}$ with the output quantity x approximates the amount of raw material required to machine a workpiece with a given number of workpiece features. [FAND05; GUTE83]

The indirect relation considers the technological properties of the machine tool to derive the consumption function. As discussed in the last section, a maximum number of orders $o_{crit,MT,l}$ machinable during the reference period T may be identified for the l-th step of the transformation process. If the number of orders is increased beyond that limit, multi-technology platforms are paralleled to be capable of processing the required output quantities. The consumption of some factors like the amount of lubricating oil depends on the number of paralleled machine tools $L_{para,MT}$. Hence, the indirect production coefficient $a_{\gamma,i,MT}$ of these consumables is multiplied by the number of paralleled machine tools to approximate the amount of consumption during the reference period T. [GUTE83, p. 225 et sqq.; FAND05, p. 105 et seq].

The general mathematical expression of a consumption function of an integrated manufacturing system needs to consider a term, which describes the direct relation of a consumable γ to output x, and an indirect term, which models the amount consumable required to operate $L_{para,IMS}$ paralleled multi-technology platforms:

$$r_{\gamma,IMS} = \overbrace{a_{\gamma,d,IMS} \cdot x}^{\text{direct}} + \overbrace{a_{\gamma,i,IMS} \cdot L_{para,IMS}(x)}^{\text{indirect}} \tag{6.10}$$

The modelling of consumption within the segregated manufacturing system stipulates the description of the relation between consumable γ and output x of each machine tool. Subsequently, this description will be extended to all paralleled single-technology stand-alone machine tools within the segregated manufacturing system.

The factor consumption at the stage l within the serial chain $r_{\gamma,l}$ depends on the number of paralleled single-technology machine tools $L_{para,l}$ required to produce the output x. Furthermore, only the workload fraction f_l is machined at stage l:

$$r_{\gamma,l} = x \cdot a_{\gamma,d,l} \cdot f_l + a_{\gamma,i,l} \cdot L_{para,l} \tag{6.11}$$

Finally, the consumption of all stages of the serial chain is added up to determine the factor consumption within the whole segregated manufacturing system:

$$r_{\gamma,SMS} = \sum_{l=1}^{L_{serial,SMS}} r_{\gamma,l} = x \cdot a_{\gamma,d,SMS} + \sum_{l=1}^{L_{serial,SMS}} a_{\gamma,i,l} \cdot L_{para,l} \tag{6.12}$$

6.1.2 Profitability function

The identification of the efficient manufacturing system from a set of alternatives requires the definition of efficiency criteria. Production theory distinguishes a weak and a strong efficiency criterion. According to the weak efficiency criterion the efficient manufacturing system is characterized by a minimum amount of input to produce a given output. However, if multiple inputs of distinct nature are required to manufacture the output, the input amounts need to be valued in monetary terms to decide which production is preferable. The strong efficiency criterion refers to the manufacturing system with the least cost which is determined by valuing the input. [FAND05, p. 48]

In section 6.1 the domain of market niche development and the domain of broad market application were distinguished. In the domain of market niche development the integrated manufacturing system is the only production system capable of machining the workpieces according to the quality requirements. Here, efficiency criteria, which intend to support a decision between two alternative systems must fail since there is no alternative to selecting the multi-technology platform. Moreover, it might not be economically efficient to manufacture a certain type of workpiece just because there is no technologically feasible alternative. If the cost exceeds the value creation by the multi-technology platform, the production will be in deficit obviously. Thus, apart from valuing costs a valuation of the output is required.

The mutual consideration of value and cost creation leads to the idea of linking production theory to profitability theory, which is a key demand of Dyckhoff in his appeal for a reconception of classical production theory [DYCK03, p. 715 et seq.]. The profitability π_j of a manufacturing system j is equal to the difference of value and cost:

$$\pi_j(x) = V_j(x) - C_j(x) \tag{6.13}$$

The following section will specify the value function V(x) and the cost function C(x).

Value function

The value of output V may be approximated by multiplying the number of orders o machined within the reference period T, the number of workpieces per lot m, the number of features per workpiece n, and the value creation per feature v.

$$V(x) = o \cdot m \cdot n \cdot v = x \cdot v \tag{6.14}$$

Cost function

The total cost C_j of a manufacturing system during the reference period T may be split into costs incurred by the potential factors $C_{pot,j}$ and the costs of the consumables $C_{con,j}$, see figure 6.6. As elaborated in section 6.1.1 potential factors are all elements of the production system that provide the capacity for the stepwise transformation of raw material into the final product. Among those factors are the manufacturing system and the operators, which will be considered by the cost $C_{sys,j}$ and $C_{oper,j}$ respectively. These costs depend on the number of paralleled machine tools $L_{para,j}$. But also further overhead costs C_{over} e.g. for the production facilities or the management need to be covered by the value creation of the workpieces. These costs are independent of the considered manufacturing system.

In case of manufacturing technology integration the system cost $C_{sys,IMS}$ depends on the cost of a single multi-technology platform $c_{MT,IMS}$ and the number of paralleled platforms $L_{para,IMS}$.

$$C_{sys,IMS} = c_{MT,IMS} \cdot L_{para,IMS} \tag{6.15}$$

The cost of a single multi-technology platform during the reference period T embraces the cost of calculatory depreciation $c_{MT,D,IMS}$, imputed interest $c_{MT,I,IMS}$, maintenance cost $c_{MT,M,IMS}$, and occupancy cost $c_{MT,O,IMS}$. The calculation of the individual cost components may be found in [KLOC08, p. 383 et seq.].

$$c_{MT,IMS} = c_{MT,D,IMS} + c_{MT,I,IMS} + c_{MT,M,IMS} + c_{MT,O,IMS} \tag{6.16}$$

In case of manufacturing technology segregation the system cost $C_{sys,SMS}$ may be determined through summing up the product of the number of paralleled machine tools $L_{para,l}$ and their cost at each stage of the transformation process.

$$C_{sys,SMS} = \sum_{l=1}^{L_{Serial,SMS}} L_{para,l} \cdot c_{MT,SMS,l} \tag{6.17}$$

The operator costs $C_{oper,j}$ are calculated similar to the system costs:

$$C_{oper,IMS} = c_{oper,IMS} \cdot L_{para,\ IMS} \tag{6.18}$$

$$C_{oper,SMS} = \sum_{l=1}^{L_{Serial,SMS}} L_{para,l} \cdot c_{oper,SMS,l} \tag{6.19}$$

The cost for a consumable γ is determined by multiplying the factor consumption r_γ by its factor price q_γ. The total cost for consumables C_{con} is equal to the sum of the individual consumption of all Γ consumables:

$$C_{con,j} = \sum_{\gamma=1}^{\Gamma} q_\gamma \cdot r_\gamma \tag{6.20}$$

In case of the integrated manufacturing system, this cost may be split into a part of direct consumption cost $C_{con,d,IMS}$ which depends on the output x, and the indirect consumption cost $C_{con,i,IMS}$ which depends on the number of paralleled multi-technology platforms $L_{para,IMS}$.

$$C_{con,IMS} = x \cdot \overbrace{\sum_{\gamma=1}^{\Gamma} q_\gamma \cdot a_{\gamma,d,IMS}}^{c_{con,d,IMS}} + L_{para,IMS}(x) \cdot \overbrace{\sum_{\gamma=1}^{\Gamma} q_\gamma \cdot a_{\gamma,i,IMS}}^{c_{con,i,IMS}} \tag{6.21}$$

For the segregated manufacturing system:

$$\begin{aligned} C_{con,SMS} &= x \cdot \overbrace{\sum_{\gamma=1}^{\Gamma} q_\gamma \cdot a_{\gamma,d,SMS}}^{c_{con,d,SMS}} + \sum_{\gamma=1}^{\Gamma} q_\gamma \cdot \sum_{l=1}^{L_{serial,SMS}} L_{para,l}(x) \cdot a_{\gamma,i,l} \\ &= x \cdot c_{con,d,SMS} + \sum_{l=1}^{L_{serial,SMS}} L_{para,l}(x) \cdot \sum_{\gamma=1}^{\Gamma} q_\gamma \cdot a_{\gamma,i,l} \end{aligned} \tag{6.22}$$

The recent considerations show that the cost of potential factors $C_{pot,j}$ as well as the cost of consumption factors $C_{con,j}$ depend partly on the number of paralleled machine tools $L_{para,j}$. Subsequently, such costs are referred to as variable indirect costs $C_{v,i,j}$, because they depend indirectly on the output quantity x:

$$C_{v,i,j}(x) = C_{sys,j} + C_{oper,j} + C_{con,i,j} \tag{6.23}$$

In case of the integrated manufacturing system the variable indirect cost function is determined by the following equation:

$$C_{v,i,IMS}(x) = L_{para,IMS}(x) \cdot \overbrace{\left(c_{MT,IMS} + c_{oper,IMS} + c_{con,i,IMS}\right)}^{c_{v,i,IMS}} \tag{6.24}$$

For the segregated manufacturing system the calculation of the variable indirect cost $C_{v,i,SMS}$ is more complex because it depends on the number of paralleled machine tools at the l-th stage of the transformation process:

$$C_{v,i,SMS}(x) = \sum_{l=1}^{L_{serial,SMS}} L_{para,l}(x) \cdot \overbrace{\left[c_{MT,SMS,l} + c_{oper,SMS,l} + c_{con,i,SMS,l}\right]}^{c_{v,i,SMS,l}} \tag{6.25}$$

Apart from indirect variable cost $C_{v,i,j}$ one may distinguish direct variable costs $c_{v,d,j}$ which depend directly on the number of the features manufactured during the reference period T, see figure 6.6. Variable direct costs are solely linked to the direct consumption cost $C_{con,d,j}$.

Fix costs C_f remain constant no matter how much output x the system generates. The recent consideration indicates that only the overhead cost may be considered to be constant over the output x. Furthermore, fix costs are independent of the considered production alternative.

Thus, the total cost of a production system C_j is described by fixed costs C_f as well as the variable direct and variable indirect cost, $c_{v,i,j}$ and $c_{v,d,j}$ respectively.

$$C_j = C_f + C_{v,j} = C_f + C_{v,i,j}(x) + c_{v,d,j} \cdot x \tag{6.26}$$

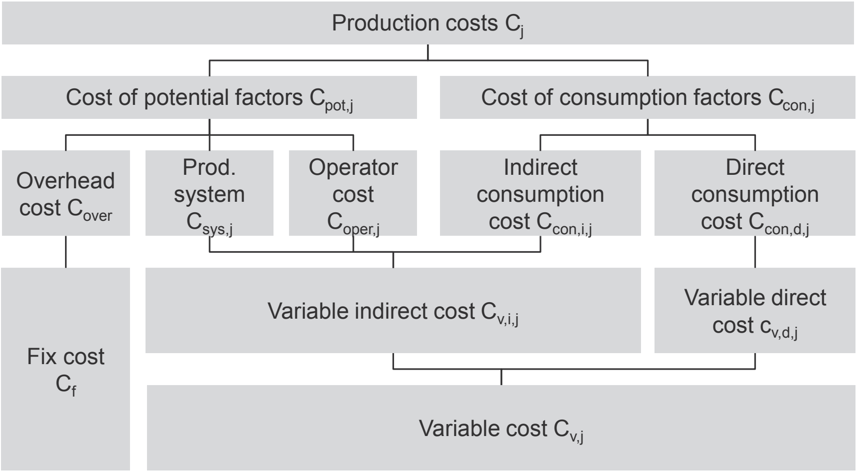


Figure 6.6: Classification scheme of production costs

Klassifikationsschema für die Produktionskosten

Alternatively, a common representation of production cost relates the total cost C_j to the amount of output x to derive piece costs $\hat{c}_j$:

$$\hat{c}_j = \frac{C_j}{x} = \frac{C_f}{x} + \frac{C_{v,i,j}}{x} + c_{v,d,j} \tag{6.27}$$

6.1.3 Throughput time function

The throughput time $t_{tp,j}$ describes the duration an order remains within the manufacturing system i.e. the time until all processing steps have been completed. In case of a segregated production system the throughput time consists of the three components transportation time $t_{tr,l}$, waiting time before machining $t_{wbm,l}$, as well as the operation time $t_{op,l}$, see figure 6.4.

Throughput times depend significantly on the waiting times before processing. In a real production environment waiting times often exceed operation times by a factor of more than three. The average duration of waiting before processing may be estimated based on mathematical queuing theory. The most common queuing model is the M/M/1 model, which assumes that interarrival times between orders are exponentially distributed. [NYHU09, p. 37; GROS08, p. 53]

If the manufacturing system consists of a single machine tool the average waiting time before processing t_{wbl} may be determined by the following relationship, where λ is the so-called birth rate of orders and U_m is the mean utilization of the machine tool: [GROS08, p. 62]

$$t_{wbl} = \frac{U_m}{\lambda \cdot (1 - U_m)} \tag{6.28}$$

with

$$\lambda = \frac{o}{\hat{T}_{op}} \tag{6.29}$$

Figure 6.7 illustrates the relationship between the mean utilization U_m of a machine tool and the average waiting time before processing t_{wbp}.

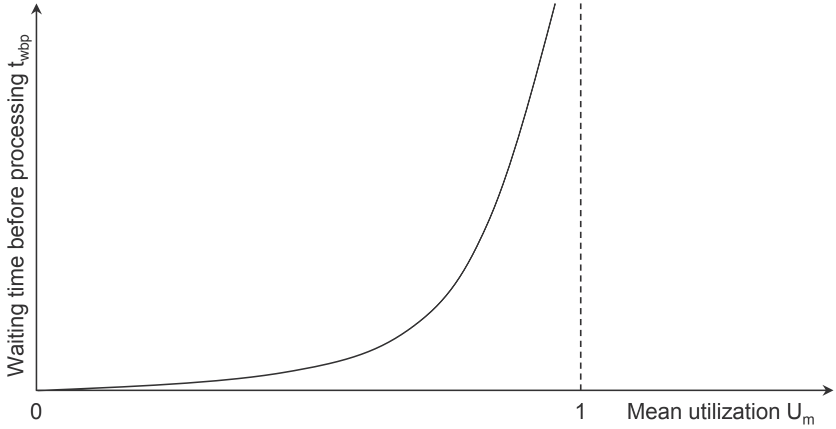


Figure 6.7: Waiting time before processing over mean utilization

Wartezeit vor der Bearbeitung über der mittleren Auslastung

As illustrated in figure 6.3 the integrated and the segregated manufacturing system may contain paralleled machine tools. The influence of paralleled machine tools on throughput times may be studied by the so-called M/M/c queuing model. The M/M/c will be adapted from literature in the following to allow a comparison of throughput times between integrated and segregated manufacturing systems. According to the M/M/c queuing model, the average waiting time before processing $t_{wbp,l}$ depends on the number of paralleled machine tools in each stage of the production process $L_{para,l}$, the mean utilization of a work station U_m as well as the operation time $t_{op,l}$. [GROS08, p. 69]

$$t_{wbp,l} = \left(\frac{U_m^{L_{para,l}}}{L_{para,l}! \cdot \frac{L_{para,l}}{t_{op,l}} \cdot (1 - \rho_l)^2} \right) \cdot p_{0,l} \tag{6.30}$$

with

$$p_{0,l} = \left(\frac{U_m^{L_{para,l}}}{L_{para,l}! \cdot (1 - \rho_l)} + \sum_{k=0}^{L_{para,l}-1} \frac{U_m^k}{k!} \right)^{-1} \tag{6.31}$$

and

$$\rho_l = \frac{o \cdot t_{op,l}}{\hat{T}_{op,l}} \tag{6.32}$$

The average throughput time of the segregated manufacturing system is the sum of the throughput time of each machine:

$$t_{tp,SMS} = \sum_{l=1}^{L_{serial,SMS}} t_{tp,l} = \sum_{l=1}^{L_{serial,SMS}} \left(t_{tr,l} + t_{wbp,l} + t_{op,l} \right) \tag{6.33}$$

This equation may be simplified to describe the throughput time of the integrated production system, since manufacturing technology integration shortens the logistic chain to a single stage:

$$t_{tp,IMS} = t_{tr,IMS} + t_{wbp,IMS} + t_{op,IMS} \tag{6.34}$$

By definition, the transportation time to the first machine of the segregated system $t_{tr,1}$ as well as the transportation time to the multi-technology platforms $t_{tr,IMS}$ is set to zero. These times are not intrinsic system properties of the integrated or segregated production system but rather of the superordinate production environment. Thus, these time components are of no importance to the comparison of manufacturing technology integration and segregation.

$$t_{tr,1} = t_{tr,IMS} = 0 \tag{6.35}$$

6.2 Derivation of efficiency conditions

In the following section the conditions under which integrated manufacturing systems may be operated efficiently in comparison to segregated manufacturing systems are derived. For this the efficiency criteria productivity, profitability, and throughput time are considered. Section 6.2.1 derives the absolute productivity limit of an integrated and a segregated manufacturing system. The conditions under which integrated manufacturing systems possess a higher productivity than segregated manufacturing systems are discussed in section 6.2.2. Based on the absolute profitability criterion the break-even output quantity and the required value creation per workpiece feature are determined in section 6.2.3. Section 6.2.4 elucidates the conditions under which integrated manufacturing systems are more profitable than segregated manufacturing systems. In section 6.2.5 the conditions of smaller throughput times of the integrated manufacturing system in comparison to the segregated manufacturing system are discussed.

6.2.1 Absolute productivity

The term “productivity” is defined as the “ratio of what is produced to what is required to produce it”. This definition will be concretised by the subsequent considerations to derive the conditions under which the productivity of an integrated manufacturing system is higher than the productivity of a segregated manufacturing system.

In the following, the feasible output amount of an integrated and a segregated manufacturing system during the reference period T is determined. However, since the output amount of a segregated and an integrated manufacturing system is deliberately scalable by adding single-technology machine tools or multi-technology platforms to the respective systems, a reference number of system elements needs to be introduced for each system to enable a representative comparison. This reference number is predicated on the smallest amount of system elements required to machine all geometrical features of a given workpiece spectrum. In case of manufacturing technology integration, by definition a single multi-technology platform suffices to perform the required operations to machine all geometrical features on a workpiece, whereas a single serial line of unparalleled single-technology machine tools represents the minimum amount of system elements to execute aforesaid operations in case of manufacturing technology segregation. The term “productivity” as applied in this thesis may be defined as follows:

The productivity of the integrated manufacturing system describes the maximum feasible output in terms of features $x_{crit,IMS}$ of a single multi-technology platform during the reference period:

$$x_{crit,IMS} = \overbrace{\text{floor}\left[\frac{\hat{T}_{op,MT}}{t_{co,IMS} + m \cdot \left(t_{wc,IMS} + n \cdot t_{p,IMS}\right)}\right]}^{o_{crit,IMS}} \cdot m \cdot n \tag{6.36}$$

The productivity of the segregated manufacturing system describes the maximum feasible output in terms of features $x_{crit,SMS}$ of a single serial line of unparalleled single-technology machine tools during the reference period. It depends on the workload fraction f_{max} of the bottleneck machine of the segregated manufacturing system.

$$x_{crit,SMS} = \overbrace{\text{floor}\left[\frac{\hat{T}_{op,MT}}{t_{co,SMS} + m \cdot \left(t_{wc,SMS} + n \cdot f_{max} \cdot t_{p,SMS}\right)}\right]}^{o_{crit,SMS}} \cdot m \cdot n \tag{6.37}$$

For a given number of orders o and workpiece features n the maximum lot size m of a machine tool may be determined by the following expression based on equation (6.36) and (6.37).

$$m \leq \mu_{abs,j}(o,n) = \frac{\widehat{T}_{op,j} - o \cdot t_{co,j}}{o \cdot \left(t_{wc,j} + n \cdot f_l \cdot t_{p,j}\right)} \tag{6.38}$$

The expression states that at its absolute productivity limit a machine tool may either process small lot sizes of workpieces with a large number of features or large lot sizes of workpieces with few features, see figure 6.8.

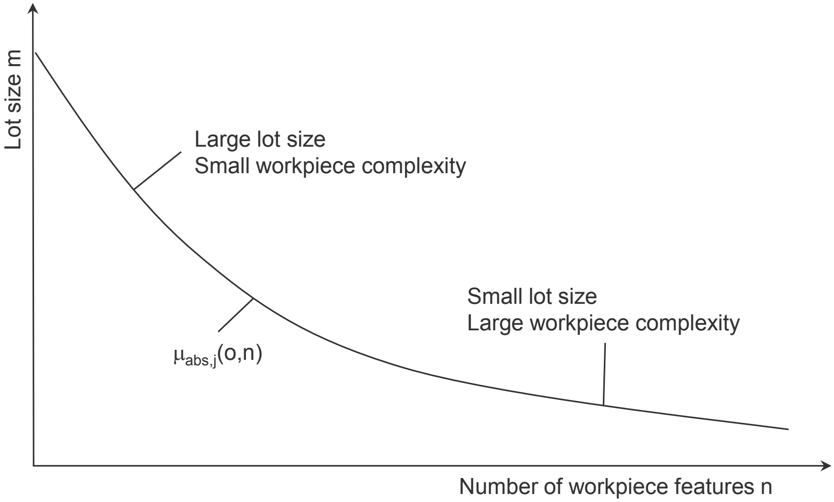


Figure 6.8: Illustration of the absolute productivity limit
Darstellung der absoluten Produktivitätsgrenze

6.2.2 Relative productivity

The study of absolute productivity and the characteristic μ_{abs} showed that at the productivity limit an integrated manufacturing system may either produce large lot sizes of products with few features or small lot sizes of products with multiple features. To reflect which of these options is more favourable for manufacturing technology integration, the relative productivity of an integrated manufacturing system in comparison to a segregated manufacturing system will be discussed.

The conditions under which the productivity of the integrated manufacturing system is higherer than the productivity of the segregated manufacturing system will be derived based on:

$$x_{crit,IMS} > x_{crit,SMS} \tag{6.39}$$

In order to facilitate the algebraic transformations the rounding operations in equations (6.36) and (6.37) are neglected. Under this simplifying assumption the condition $x_{crit,IMS} > x_{crit,SMS}$ may be rewritten in terms of lot size m, number of features n, and the operation time components t_{co}, t_{wc}, and t_p:

$$\frac{\hat{T}_{op,IMS}\cdot m\cdot n}{t_{co,IMS} + m\cdot\left(t_{wc,IMS} + n\cdot t_{p,IMS}\right)} > \frac{\hat{T}_{op,SMS}\cdot m\cdot n}{t_{co,SMS} + m\cdot\left(t_{wc,SMS} + n\cdot f_{max}\cdot t_{p,SMS}\right)} \tag{6.40}$$

Basic algebraic transformation leads to the following expression:

$$-\overbrace{\left(\frac{t_{co,SMS}}{\hat{T}_{op,SMS}} - \frac{t_{co,IMS}}{\hat{T}_{op,IMS}}\right)}^{\Delta\tau_{co}} < m\cdot\left[\overbrace{\left(\frac{t_{wc,SMS}}{\hat{T}_{op,SMS}} - \frac{t_{wc,IMS}}{\hat{T}_{op,IMS}}\right)}^{\Delta\tau_{wc}} + n\cdot\overbrace{\left(f_{max}\cdot\frac{t_{p,SMS}}{\hat{T}_{op,SMS}} - \frac{t_{p,IMS}}{\hat{T}_{op,IMS}}\right)}^{\Delta\tau_{p}}\right] \tag{6.41}$$

The characteristics $\Delta\tau_{co}$ and $\Delta\tau_{wc}$ describe the difference of the operation time components weighted by the respective maximum operation time $\hat{T}_{op}$ during the reference period T. In contrast to $\Delta\tau_{co}$ and $\Delta\tau_{wc}$, the term $\Delta\tau_p$ comprises the workload fraction of the bottleneck machine f_{max} as well.

The characteristic μ_{rel} describes all combinations of lot size m and number of features n that lead to similar productivity on the integrated and the segregated manufacturing system. Hence, the characteristic μ_{rel} divides the plane spanned by lot size m and number of features n into a region in which the productivity of the integrated manufacturing system is higher and a region in which it is smaller than the productivity of the segregated manufacturing system.

$$\mu_{rel}(n) = -\frac{\Delta\tau_{co}}{\Delta\tau_{wc}+\Delta\tau_{p}\cdot n} \tag{6.42}$$

Dependent on the sign of the characteristics $\Delta\tau_{co}$, $\Delta\tau_{wc}$, and $\Delta\tau_p$ the characteristic $\mu_{rel}(n)$ may assume eight distinct progressions over the number of workpiece features n. These eight cases are depicted in principle in figure 6.9.

In case 1, the reduction of changeover time t_{co}, workpiece change time t_{wc}, and processing time t_p due to manufacturing technology integration are sufficiently high such that the three characteristics $\Delta\tau_{co}$, $\Delta\tau_{wc}$, and $\Delta\tau_p$ assume a value greater than zero. Consequently, the productivity of the integrated manufacturing system is higher than the productivity of the segregated manufacturing system for any number of workpiece features n and any lot size m. In the complementary case 8 all three characteristics are negative. Here, the productivity of the integrated manufacturing system is smaller than the productivity of the segregated manufacturing system for any lot size m and number of features n.

Under all other circumstances a region of higher and a region of smaller productivity exists within the plane spanned by number of workpiece features n and lot size m. Case 2 and case 7, case 3 and case 6, as well as case 4 and case 5 are complementary to each other. The regions of higher productivity correlate to the signs of the characteristics $\Delta\tau_p$, $\Delta\tau_{wc}$, and $\Delta\tau_{co}$.

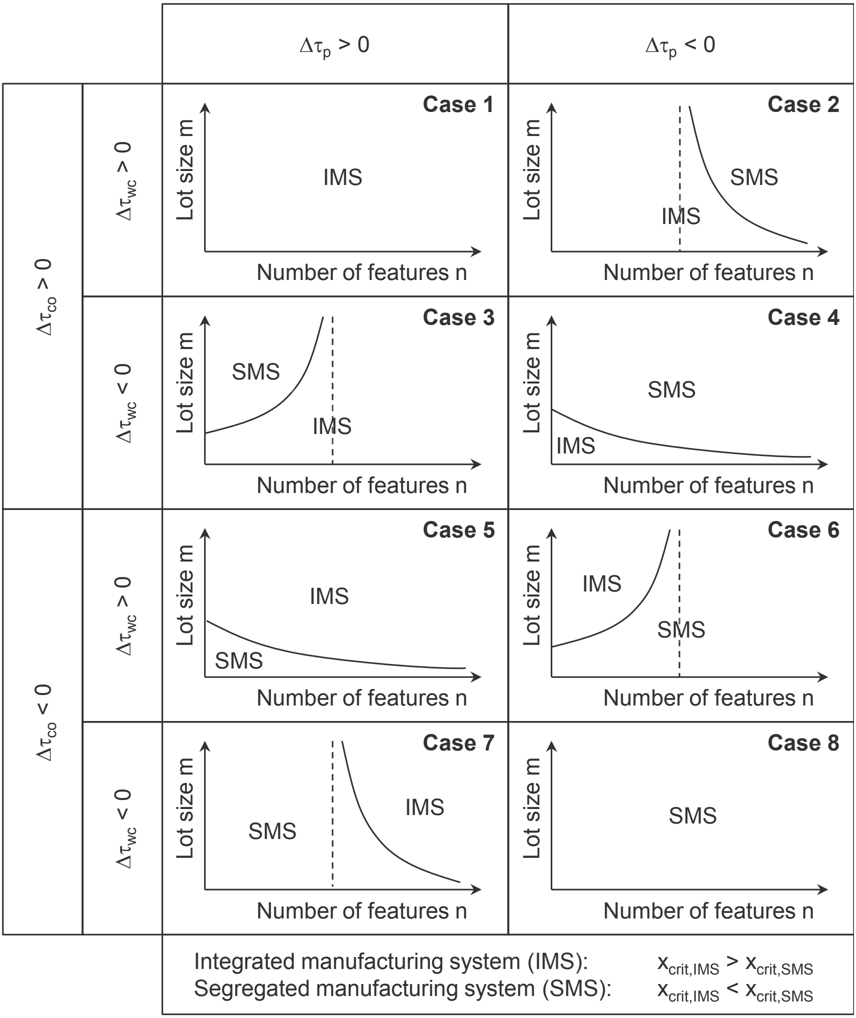


Figure 6.9: Distinction of cases of relative productivity

Fallunterscheidung der relativen Produktivität

Higher productivity in a domain of small lot size and a small number of workpiece features stipulates a significant reduction of changeover time t_{co} through manufacturing technology integration such that the characteristic $\Delta\tau_{co}$ becomes positive (compare case 4). The attributes “small” lot size and “large” number of workpiece features may be quantified by considering expression (6.42). A positive value of the characteristic $\Delta\tau_{wc}$ which is linked to workpiece change time t_{wc} correlates to a higher productivity of the integrated manufacturing system in a domain of large lot size but small number of workpiece features (compare case 6). A reduction of processing time through manufacturing technology integration that leads to a positive characteristic $\Delta\tau_p$ possesses a particular impact on productivity in a domain characterised by a large number of workpiece features n and large lot size m (compare case 7).

In case 2, case 3, and case 5 two of the three characteristics are greater than zero. Under these circumstances the regions of higher productivity of the integrated manufacturing system expand with regard to lot size m and number of workpiece features n depending on the two characteristics that are greater than zero.

Expression (6.41) and figure 6.9 provide a scheme to generically compare the productivity of two manufacturing systems. To identify the most probable case of relative productivity of an integrated and a segregated manufacturing system the likelihood of positive characteristics $\Delta\tau_p$, $\Delta\tau_{wc}$, and $\Delta\tau_{co}$ must be discussed in the following.

The characteristic $\Delta\tau_p$ is greater than zero, if the processing time of the integrated system $t_{p,IMS}$ is smaller than the subsequent expression:

$$\Delta\tau_p > 0 \Leftrightarrow t_{p,IMS} < \overbrace{\frac{\hat{T}_{op,IMS}}{\hat{T}_{op,SMS}}}^{\omega} \cdot f_{max} \cdot t_{p,SMS} = f_{p,red} \cdot t_{p,SMS} \tag{6.43}$$

The expression indicates that a simple reduction of processing time $t_{p,IMS}$ of the integrated manufacturing system compared to the processing time of the segregated system $t_{p,SMS}$ may not be sufficient to assure a positive value of $\Delta\tau_p$. Apart from the processing time of the segregated system $t_{p,SMS}$, a positive value of $\Delta\tau_p$ stipulates the consideration of the ratio of maximum operation times ω as well as the compensation of the workload fraction of the bottleneck machine f_{max}. These two factors compose the processing time reduction factor $f_{p,red}$.

According to equation (6.1) and (6.6), the maximum operation time of a machine tool $\hat{T}_{op,MT}$ depends on the failure probability p_{MT}, the maximum mean utilization $U_{m,max}$ and the duration of the reference period T. While the maximum mean utilization $U_{m,max}$ and the duration of the reference period do not differ between the segregated and the integrated manufacturing system, considerable differences may exist with regard to the failure probabilities. Therefore, the ratio ω may be expressed in terms of the failure probabilities:

$$\omega = \frac{1 - p_{IMS}}{1 - p_{SMS}} \tag{6.44}$$

In general, it seems reasonable to assume that the failure probability of a multi-technology platform exceeds the failure probability of a single-technology machine tool due to its higher complexity, if apart from the number of installed manufacturing technologies the same level of technological advancement is existent. If however the failure probabilities of multi-technology platforms are higher, the operation time ratio T_{op} always assumes values smaller than one.

Based on these considerations the required reduction of processing time by means of manufacturing technology integration $\Delta t_{p,mti}$ may be introduced:

$$t_{p,IMS} = t_{p,SMS} - \Delta t_{p,ti} \tag{6.45}$$

The required, percentagewise reduction of processing time $\Delta t_{p,IMS,\%}$ is determined by the following expression:

$$\Delta t_{p,IMS,\%} = \frac{\Delta t_{p,mti}}{t_{p,SMS}} \cdot 100\ \% = (1 - f_{p,red}) \cdot 100\ \% \tag{6.46}$$

It becomes obvious that the required percentagewise reduction of processing time $\Delta t_{p,IMS,\%}$ smaller than 10 % stipulates almost no difference in failure probabilities between multi-technology platforms and the respective bottleneck machine *and* a pronounced unbalance between the workload fractions of the individual single-technology machine tools within the serial line of the segregated manufacturing system.

In reality, uneven workload distributions between machine tools are usually avoided. Furthermore, the maximum operation time ratio ω may assume values smaller than 0,98 due to differences in failure probabilities between complex multi-technology platforms and robust single-technology machine tools as discussed above. Therefore, it appears likely that the required, percentagewise reduction of processing time $\Delta t_{p,IMS,\%}$ is greater than 15 % to assure a positive value of $\Delta\tau_p$ according to expression (6.43). In the following, it will be discussed whether such a pronounced reduction of processing times is feasible through means of manufacturing technology integration.

The processing time t_p was defined in section 6.1.1 as being the sum of tool engagement time t_c, jogging time t_{jog}, and the proportional tool exchange time t_t. No difference with regard to the actual manufacturing processes exists between the segregated and the integrated manufacturing system, which signifies that the tool engagement times are equal ($t_{c,IMS} = t_{c,SMS}$). If the manufacturing processes are technologically indifferent the reduction of processing time $t_{p,IMS}$ must be accomplished solely by significantly reducing jogging time t_{jog} as well as tool exchange time t_t. However, state of the art single-technology machine tools are equipped with a variety of resources such as automatic tool change units, rapid feeding devices, etc. that are already capable of eliminating jogging and tool exchange times to large extents. Although, manufacturing technology integration may effectively reduce workpiece change time $t_{wc,IMS}$ by eliminating alignment, measuring, and clamping operations no such impact is expected with regard to jogging times t_{jog} and tool exchange times t_t. It follows that the feasible reduction of $t_{p,IMS}$ through means of manufacturing technology integration is - in most cases - insufficient to assure positive values of $\Delta\tau_p$.

$$\text{Assumption: } \Delta\tau_p < 0 \tag{6.47}$$

The characteristic $\Delta\tau_{wc}$ is greater than zero if the workpiece change time $t_{wc,IMS}$ is smaller than the workpiece change time of the segregated system $t_{wc,SMS}$ weighted by the ratio of maximum operation times ω.

$$\Delta\tau_{wc} > 0 \Leftrightarrow t_{wc,IMS} < \omega \cdot t_{wc,SMS} \tag{6.48}$$

It must be noticed that the workload fraction of the bottleneck machine f_{max} does not appear in the expression for $t_{wc,IMS}$ like in the expression for the processing time $t_{p,IMS}$, compare expression (6.43) to (6.48). Therefore, the hurdles in terms of workpiece change time reduction required to obtain a positive value of $\Delta\tau_{wc}$ are significantly lower than for required processing time reduction defined by the processing time reduction factor $f_{p,red}$.

As outlined above, workpiece change times of the integrated manufacturing system $t_{wc,IMS}$ may effectively be reduced by elimination of alignment, measuring, and clamping operations through means of manufacturing technology integration. Significant workpiece change time reductions appear particularly feasible if the bottleneck machine of the segregated manufacturing system assumes a rear position within the serial line i.e. workpiece precision obtained by previous processing steps is large. Under these circumstances it may take a significant amount of time to align, measure, and clamp the workpiece on the bottleneck machine. Subsequently, if complete machining in a single clamping is technologically feasible on a multi-technology platform, workpiece change times may be reduced significantly. To sum up, due to the low hurdles described by expression (6.42) and the opportunities to effectively reduce workpiece change times through means of manufacturing technology integration, the impact of a positive characteristic $\Delta\tau_{wc}$ will be outlined in further considerations.

$$\text{Assumption } \Delta\tau_{wc} > 0 \tag{6.49}$$

The characteristic $\Delta\tau_{co}$ which has not been discussed so far appears in expression (6.42), too. This characteristic possesses a similar outline as the characteristic $\Delta\tau_{wc}$ as the ratio of maximum operation times ω defines the required reduction of changeover times of the integrated manufacturing system, whereas the workload fraction of the bottleneck machine f_{max} is absent:

$$\Delta\tau_{co} > 0 \Leftrightarrow t_{co,IMS} < \omega \cdot t_{co,SMS} \tag{6.50}$$

Hence, the hurdle in terms of required changeover time reduction is of a comparable magnitude as the required workpiece change time reduction, compare expression (6.48). As opposed to the workpiece change time $t_{wc,IMS}$ it is not quite evident why manufacturing technology integration should effectively reduce changeover times $t_{co,IMS}$ in comparison to the changeover times of the bottleneck machine within the segregated manufacturing system $t_{co,SMS}$. Moreover, it seems reasonable to assume that the complexity of multi-technology platforms exceeds the complexity of single-technology machine tools. In consequence, the changeover time of an integrated system $t_{co,IMS}$ may actually be higher than those of the respective bottleneck machine within segregated manufacturing systems which leads to a negative value of the characteristic $\Delta\tau_{co}$. Thus, the case of $\Delta\tau_{co} < 0$ will be discussed in the following.

$$\text{Assumption: } \Delta\tau_{co} < 0 \tag{6.51}$$

Now, the assumptions drawn may be compared to the cases distinguished by figure 6.9. The goal is to determine whether the productivity of the integrated manufacturing system exceeds the productivity of the segregated manufacturing system for large or for small lot sizes.

The combination ($\Delta\tau_p < 0$, $\Delta\tau_{wc} > 0$, $\Delta\tau_{co} < 0$) corresponds to case 6. In case 6 the characteristic μ_{rel} possesses a pole which may be determined by studying the denominator ψ of expression (6.42).

$$\psi = \Delta\tau_{wc} + n \cdot \Delta\tau_p = 0 \Leftrightarrow n < \nu = -\frac{\Delta\tau_{wc}}{\Delta\tau_p} \tag{6.52}$$

For the assumptions drawn ($\Delta\tau_p < 0$, $\Delta\tau_{wc} > 0$) the characteristic ν assumes a value greater than zero. If the number of workpiece features n is smaller than the characteristic ν the characteristic ψ assumes a value greater than zero. The productivity of the integrated manufacturing system is greater than the productvitiy of the segregated manufacturing system if the number if workpiece features n are smaller than the characteristic ν and the lot size is greater than the characteristic μ_{rel}.

$$x_{crit,IMS} > x_{crit,SMS} \Leftrightarrow n < \nu = -\frac{\Delta\tau_{wc}}{\Delta\tau_p} \wedge m > \mu_{rel} = -\frac{\Delta\tau_{co}}{\Delta\tau_{wc}+\Delta\tau_p \cdot n} \tag{6.53}$$

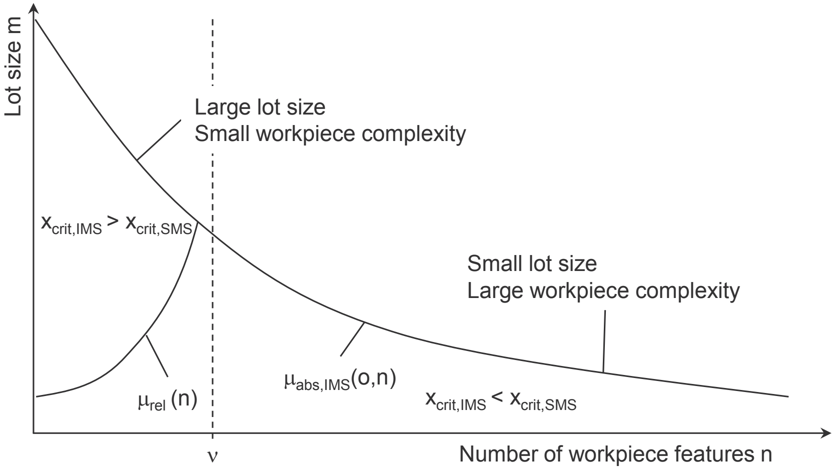


Figure 6.10: Illustration of the absolute and the relative productivity limit
Darstellung der absoluten und der relativen Produktivitätsgrenze

This finding contradicts the prevailing notion that manufacturing technology integration is in particular suitable for workpieces with many features in small lot sizes. Although a significant reduction of workpiece change time may enhance the productivity of integrated manufacturing systems the recent consideration illustrate the obstacles to obtain a higher productivity than segregated manufacturing systems. This is in particular due to the fact that the workload may be machined in parallel within the serial chain of single-technology machine tools of the segregated manufacturing system while it was assumed that the whole workload is carried by a single multi-technology platform within the integrated manufacturing system. Inevitably, it will be assumed for the subsequent considerations that the productivity of a single multi-technology platform is smaller than the productivity of a serial line of unparalleled single-technology machine tools within the segregated manufacturing system. This signifies that multi-technology platforms must be paralleled to compete with segregated manufacturing systems in terms of productivity.

$$\text{Assumption: } x_{crit,IMS} < x_{crit,SMS} \tag{6.54}$$

6.2.3 Absolute profitability

Absolute profitability is a prerequisite for the propitiousness of integrated manufacturing systems within the domain of market niche development and the domain of broad market application, compare figure 6.2. The criterion of absolute profitability reflects that a rational producer is only willing to manufacture workpieces with the integrated manufacturing system if the value creation V_{IMS} exceeds the production costs C_{IMS}:

$$V_{IMS} > C_{IMS} \Leftrightarrow \pi_{IMS} > 0 \tag{6.55}$$

In the following the conditions for a profitability π_{IMS} greater than zero are examined. Figure 6.11 depicts the value creation V_{IMS} and the total cost function C_{IMS} over the output x during the reference period T. The total cost function C_{IMS} possesses evenly spaced steps to account for the parallelisation of multi-technology platforms within the integrated manufacturing system. Parallelisation of multi-technology platforms is required as soon as the output x exceeds the productivity of a single multi-technology platform $x_{crit,IMS}$, see figure 6.11.

The condition for profitability greater than zero ($\pi > 0$) can be identified by considering figure 6.11. Firstly, the inclination of the value creation function v must at least exceed the mean inclination of the total cost function $\alpha_{C,weak}$. Otherwise, the value creation function V_{IMS} and the total cost function C_{IMS} do not intersect and the condition $\pi_{IMS} > 0$ is not fulfilled, see case III in figure 6.11.

$$v > \alpha_{C,weak} = \frac{c_{v,i,IMS}}{x_{crit,IMS}} + c_{v,d,IMS} \tag{6.56}$$

This is a *weak* condition of absolute profitability because there might be multiple intersections between the value creation function V_{IMS} and the total cost function C_{IMS}. In consequence a continuous transition might prevail between regions of absolute economic efficiency and regions of deficit due to the step-like total cost function, see case II in figure 6.11.

A single intersection between the value creation function V_{IMS} and the total cost function C_{IMS} is only feasible for the first multi-technology platform if the inclination of the value creation function exceeds the dotted line marked with $\alpha_{C,strong}$. This will be referred to as the strong condition of absolute profitability:

$$v > \alpha_{C,strong} = \frac{C_f + 2 \cdot c_{v,i,IMS}}{x_{crit,IMS}} + c_{v,d,IMS} \tag{6.57}$$

Furthermore, the strong condition of absolute profitability demands that the output x exceeds break-even values like $x_{be,IMS}$ in figure 6.11. While a single break-even value $x_{be,IMS}$ characterizes case I, a multitude of such values appears in case II due to the continuous transition of the value creation and the total cost function, see figure 6.11.

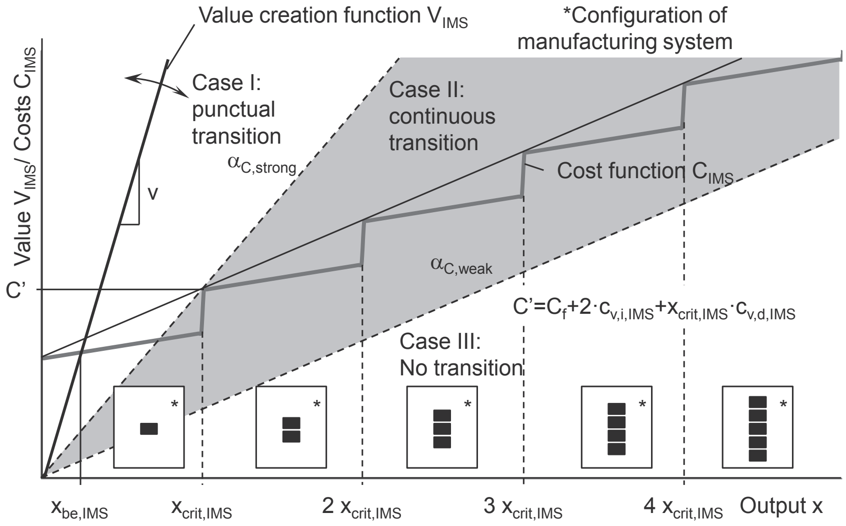


Figure 6.11: Comparison of value creation function and total cost function

Gegenüberstellung der Wertschöpfungs- und der totalen Kostenfunktion

The consideration of absolute profitability allows concluding two conditions of economic efficiency of manufacturing technology integration. Firstly, the value creation per feature v should be high enough such that only a punctual transition between the value creation and the total cost function occurs ($v > \alpha_{C,strong}$). Since parallelisation of multi-technology platforms must be considered this means that integrated manufacturing systems should produce *high value products*. The attribute "high value" is defined by expression (6.57). Secondly, the output x must exceed the break-even output x_{be}. If condition (6.57) is fulfilled the absolute profitability of the integrated manufacturing system increases through raising the output since the value creation function V_{IMS} and the total cost function C_{IMS} diverge. Hence, the criterion of absolute economic efficiency in combination with condition (6.57) demands that the *output x should be as high as possible*.

6.2.4 Relative profitability

Relative profitability links the absolute profitability of the integrated manufacturing system to the absolute profitability of the segregated manufacturing system. Relative profitability is a prerequisite for benefits within the domain of broad market penetration, see figure 6.2. The integrated manufacturing system is advantageous, if it yields a higher profitability than the segregated manufacturing system:

$$\pi_{IMS} > \pi_{SMS} \Leftrightarrow \pi_{IMS} - \pi_{SMS} > 0 \tag{6.58}$$

In the domain of relative profitability it is assumed that both systems produce the same type of workpieces and the quality requirements are met by either system. This is the case if the value creation per workpiece v_j is equal for both alternatives:

$$v_{IMS} = v_{SMS} \tag{6.59}$$

Furthermore, the variable direct cost $c_{v,d,j}$ are assumed to be determined by material cost rather than system cost. Thus, variable direct cost $c_{v,d,j}$ are equal for the integrated and the segregated manufacturing system.

$$c_{v,d,IMS} = c_{v,d,SMS} \tag{6.60}$$

Under assumption (6.59) and (6.60) the criterion of relative profitability may be expressed through the variable indirect cost difference $\Delta C_{v,i}$:

$$\Delta\pi = \pi_{IMS} - \pi_{SMS} = \overbrace{\Delta v}^{=0} \cdot x + \overbrace{\Delta c_{v,d}}^{=0} \cdot x + \Delta C_{v,i}(x) \tag{6.61}$$

The variable indirect cost difference $\Delta C_{v,i}$ may be expressed through equation (6.24) and (6.25):

$$\Delta C_{v,i}(x) = \overbrace{\sum_{l=1}^{L_{serial,SMS}} L_{para,l}(x) \cdot c_{v,i,SMS,l}}^{C_{v,i,SMS}(x)} - \overbrace{L_{para,IMS}(x) \cdot c_{v,i,IMS}}^{C_{v,i,IMS}(x)} \tag{6.62}$$

The conditions of relative profitability will be derived based on the variable cost difference $\Delta C_{v,i}$. Before the conditions can be expressed in mathematical terms the variable indirect cost functions $C_{v,i,IMS}$ and $C_{v,i,SMS}$ will be discussed individually. For this the variable indirect piece cost $\hat{c}_{v,i,j}$ will be considered.

Figure 6.12 depicts the evenly spaced sawtooth shape of the variable indirect piece cost function of the integrated manufacturing system $\hat{c}_{v,i,IMS}$. Figure 6.12 shows the configuration of the integrated manufacturing system, too. Multi-technology platforms are paralleled to be capable of producing an output higher than $x_{crit,IMS}$. The variable indirect piece cost converge towards the variable indirect cost of a single multi-technology platform $c_{v,i,IMS}$ divided by the critical output $x_{crit,IMS}$ for high output quantities ($x \rightarrow \infty$), see appendix 12.1.1:

$$\hat{c}_{v,i,IMS}(\infty) = \lim_{x \to \infty} \frac{C_{v,i,IMS}(x)}{x} = \frac{c_{v,i,IMS}}{x_{crit,IMS}} \tag{6.63}$$

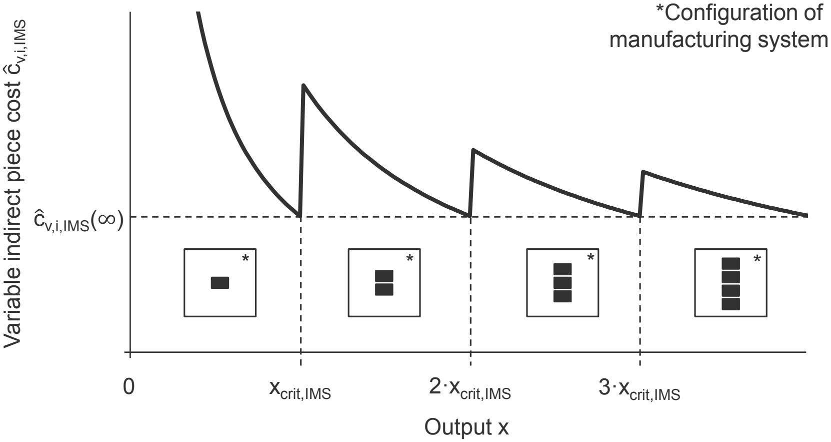


Figure 6.12: Variable indirect piece cost of integrated manufacturing system
Variable indirekte Stückkosten des integrierten Fertigungssystems

Figure 6.13 and figure 6.14 illustrate the sawtooth shapes of piece cost functions of segregated manufacturing systems $\hat{c}_{v,i,SMS}$. Two types of capacity adjustment patterns may be discerned with regard to the workload distribution between the steps of the transformation process which influences the configuration of the segregated manufacturing system. If the workload is evenly distributed, the serial chain of single-technology machine tools is paralleled as a whole to manufacture increasing output quantities, see figure 6.14. If an uneven workload distribution prevails, single-technology machine tools are added to the respective transformation step at the productivity limit successively, see figure 6.13.

At unevenly distributed workload the variable indirect piece cost of a serial line of unparalled single-technology machine tools and the variable indirect piece cost for high output quantities ($x \to \infty$) diverge. For low output quantities ($x < x_{crit,IMS}$) the variable indirect piece cost $\hat{c}_{v,i,SMS}$ of a serial line of unparalleled single-technology machine tools are equal to its variable indirect piece cost divided by x:

$$\hat{c}_{v,i,SMS}(x) = \frac{\sum_{l=1}^{L_{serial,SMS}} c_{v,i,SMS,l}}{x}, \; x < x_{crit,IMS} \tag{6.64}$$

For high output quantities ($x \to \infty$) the variable indirect piece cost converges towards the following expression, see appendix 12.1.2:

$$\hat{c}_{v,i,SMS}(\infty) = \lim_{x\to\infty} \frac{C_{v,i,SMS}(x)}{x} = \sum_{l=1}^{L_{serial,SMS}} \frac{c_{v,i,SMS,l}}{x_{crit,l}},\ x \to \infty \tag{6.65}$$

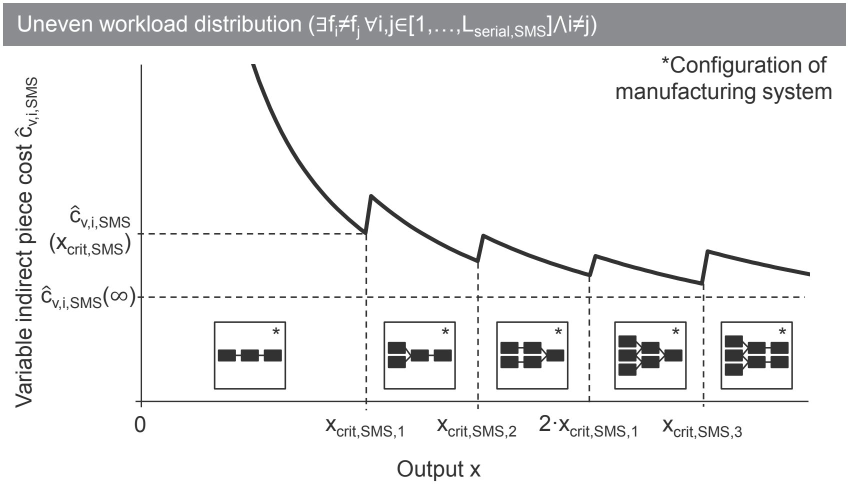


Figure 6.13: Variable indirect piece cost of segregated manufacturing system (I/II)
Variable indirekte Stückkosten des segregierten Fertigungssystems (I/II)

At evenly distributed workload the variable indirect piece cost at the productivity limit of a serial chain of unparalleled single-technology machine tool $x_{crit,SMS}$ is equal to the variable indirect piece cost for high output quantities ($x \to \infty$), see figure 6.14.

$$\hat{c}_{v,i,SMS}(x_{crit,SMS}) = \hat{c}_{v,i,SMS}(\infty) \tag{6.66}$$

Thus, the progression of variable indirect piece cost of a segregated manufacturing system possesses a similar shape as the variable indirect piece cost progression of an integrated manufacturing system, compare figure 6.12 to figure 6.14. This signifies that the hurdle for relative profitability is higher if the workload is evenly distributed between the single-technology machine tools. Hence, manufacturing technology integration should be considered in particular if the *workload is unevenly distributed*.

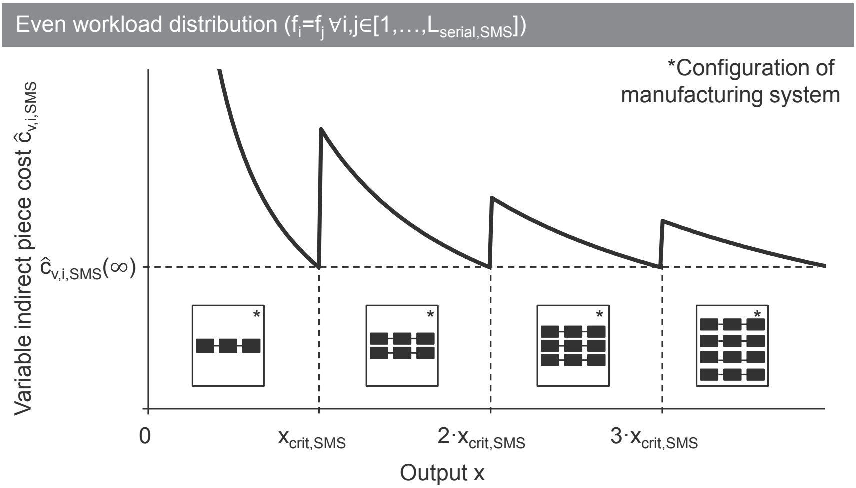


Figure 6.14: Variable indirect piece cost of segregated manufacturing system (II/II)
Variable indirekte Stückkosten des segregierten Fertigungssystems (II/II)

Based on the progressions of the variable indirect cost functions of the integrated and the segregated manufacturing system the efficiency conditions of relative profitability will be derived successively. For this, it will be assumed that the productivity of a single multi-technology platform is smaller than the productivity of a serial chain of unparalleled single-technology machine tools, see section 6.2.2:

$$\text{Assumption: } x_{crit,IMS} < x_{crit,SMS} \tag{6.67}$$

Two distinct efficiency conditions of relative profitability may be discerned with regard to the output quantity to be produced. For low output quantities ($x < x_{crit,IMS}$) the parallelization of multi-technology platforms may be neglected. Manufacturing technology integration is efficient if the variable indirect cost of a multi-technology platform $c_{v,i,IMS}$ is smaller than the cost threshold for low output quantities $\chi_{v,i,IMS}(x < x_{crit,IMS})$. This threshold is defined by the variable indirect cost of a serial chain of unparalleled single-technology machine tools, compare left diagram in figure 6.15:

$$\pi_{IMS} > \pi_{SMS} \Leftrightarrow c_{v,i,IMS} < \chi_{v,i,IMS}(x < x_{crit,IMS}) = \sum_{l=1}^{L_{serial,SMS}} c_{v,i,SMS,l} \tag{6.68}$$

For high output quantities ($x \rightarrow \infty$) the parallelization of multi-technology platforms and single-technology machine tools within the segregated manufacturing system must be considered as well. The condition of relative profitability bases on expression (6.63) and (6.65), compare right diagram in figure 6.15:

$$\pi_{IMS} > \pi_{SMS} \Leftrightarrow \frac{c_{v,i,IMS}}{x_{crit,IMS}} < \sum_{l=1}^{L_{serial,SMS}} \frac{c_{v,i,SMS,l}}{x_{crit,l}}, \; x \rightarrow \infty \tag{6.69}$$

Based on the condition of relative profitability the variable indirect cost threshold of a multi-technology platform for high output quantities $\chi_{v,i,IMS}(x \rightarrow \infty)$ may be determined by the following expression:

$$\pi_{IMS} > \pi_{SMS} \Leftrightarrow c_{v,i,IMS} < \chi_{v,i,IMS}(x \rightarrow \infty) = x_{crit,IMS} \cdot \sum_{l=1}^{L_{serial,SMS}} \frac{c_{v,i,SMS,l}}{x_{crit,l}} \tag{6.70}$$

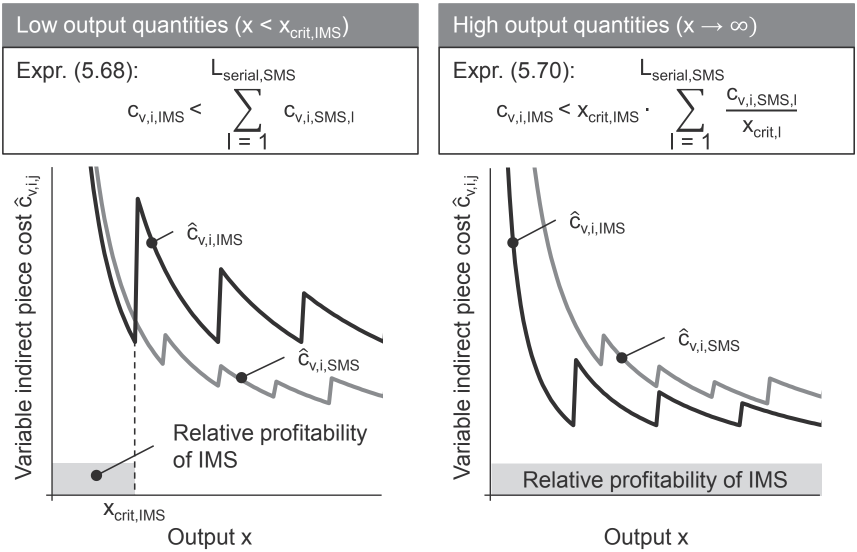


Figure 6.15: Efficiency conditions of relative profitability
Effizienzbedingungen der relativen Profitabilität

Apart from the *uneven workload distribution,* the recent consideration allows to conclude that relative profitability of integrated manufacturing systems in comparison to segregated manufacturing systems may be achieved easier if the desired output is smaller than the productivity of a single multi-technology platform $x_{crit,IMS}$. However, section 6.2.3 has shown that absolute profitability stipulates an output higher than the break-even output $x_{be,IMS}$. In consequence, manufacturing technology integration should be considered in particular for *output quantities between the break-even output $x_{be,IMS}$ and the productivity limit of the integrated manufacturing system $x_{crit,IMS}$:*

$$x_{be,IMS} < x \leq x_{crit,IMS} \tag{6.71}$$

6.2.5 Relative throughput time

Apart from profitability throughput time represents an efficiency criterion that determines the relative economic efficiency of an integrated manufacturing system in comparison to a segregated manufacturing system. An integrated manufacturing system may be considered advantageous in terms of throughput time if its average throughput time $t_{tp,IMS}$ is smaller than the average throughput time of a segregated manufacturing system $t_{tp,SMS}$:

$$t_{tp,IMS} < t_{tp,SMS} \tag{6.72}$$

The mathematical equations of the M/M/c queuing model introduced in section 6.1.3 are applied in the following to quantify the throughput time of either manufacturing system. The prerequisite for application of the queuing model is the assumption of exponentially distributed order arrival times. Figure 6.16 compares an exemplary throughput time progression over the number of orders of an integrated manufacturing system to a segregated manufacturing system consisting of three single-technology stand-alone machine tools. Due to a reduction of secondary processing times the operation time $t_{op,IMS}$ of the integrated manufacturing system is assumed to be 12,5 % smaller than the operation time $t_{op,SMS}$ of the segregated system.

Figure 6.16 shows that the progression of the throughput time function assumes a saw tooth like profile over the number of orders for the integrated manufacturing system if the number of paralleled multi-technology platforms $L_{para,IMS}$ is – as assumed - adjusted successively. In contrast to the saw tooth like progression of the piece cost functions discussed earlier the “teeth” open towards the opposite direction.

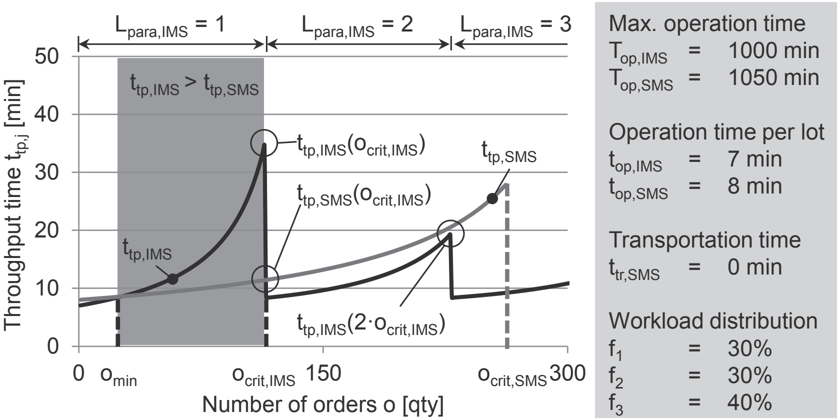


Figure 6.16: Comparison of throughput time progression over number of orders
Vergleich des Verlaufs der Durchlaufzeit über der Auftragsanzahl

This progression may be explained by the progressive increase of waiting times over the utilization of the respective system if interarrival times of orders and operation times are exponentially distributed. As soon as the second multi-technology platform is paralleled beyond $o_{crit,IMS}$, the throughput time drops because the workload may be shared evenly between the two platforms which reduces the utilization of each platform and thus the throughput times instantly.

However, due to the apportioned workload between machines on the segregated manufacturing system the utilization of the integrated manufacturing system increases at a higher slope than the utilization of the segregated manufacturing system. Therefore, throughput times of the integrated manufacturing system $t_{tp,IMS}$ may exceed throughput times of the segregated system $t_{tp,SMS}$ even if operation times of the integrated system $t_{op,IMS}$ are smaller than those of the segregated system $t_{op,SMS}$. In other words, the reduction of the logistic chain through technology integration does not necessarily lead to smaller throughput times. The likelihood of queue formation in front of multi-technology platforms also possesses consequences for the inventory. The shortening of logistic chains does not automatically lead to lower inventory and thus lower inventory associated cost. The following paragraphs discuss the ratio of operation time $\tau_{op} = t_{op,IMS}/t_{op,SMS}$ which would assure smaller throughput times on the integrated system under the assumption made by the M/M/c queuing model.

In figure 6.16 throughput times of the integrated manufacturing system $t_{tp,IMS}$ exceed throughput times of the segregated system $t_{tp,SMS}$ for a number of orders between o_{min} and $o_{crit,IMS}$ marked by the grey shaded rectangle. The highest exaggeration of throughput time appears for $o_{crit,IMS}$. If the throughput time $t_{tp,IMS}$ of the integrated system at $o_{crit,IMS}$ is smaller than the respective throughput time of the segregated system $t_{tp,SMS}(o_{crit,IMS})$, throughput times $t_{tp,IMS}$ are smaller for all orders within the range limited by $o_{crit,SMS}$.

$$t_{tp,IMS} < t_{tp,SMS} \forall o \in \{1, o_{crit,SMS}\} \Leftrightarrow t_{tp,IMS}\left(o_{crit,IMS}\right) < t_{tp,SMS}\left(o_{crit,IMS}\right) \tag{6.73}$$

This condition will be applied to derive the ratio of operation time τ_{op} required for smaller throughput times. Application of the equations introduced in section 6.1.3 leads to the following expressions for the throughput times at $o_{crit,IMS}$ of both systems:

$$t_{tp,IMS}\left(o_{crit,IMS}\right) = \frac{t_{op,IMS}}{\left(1\text{-}U_{m,max}\right)} \tag{6.74}$$

Through algebraic manipulations the following implicit inequation for the ratio τ_{op} may be derived. Solutions of this inequation for segregated manufacturing systems consisting of two and three machines are depicted in the appendix 12.1.3 and 12.1.4.

$$\frac{t_{op,IMS}}{t_{op,SMS}} < \tau_{op} = \left[\sum_{l=1}^{L_{serial,SMS}} \left(\frac{1}{f_l} - \overbrace{\frac{t_{op,SMS}}{t_{op,IMS}}}^{1/\tau_{op}} \cdot U_{m,max} \right)^{-1} + \overbrace{\frac{\sum_{l=2}^{L_{serial,SMS}} t_{tr,l}}{t_{op,SMS}}}^{\tau_{tr,SMS}} \right] \cdot \left(1\text{-}U_{m,max}\right) \tag{6.75}$$

Figure 6.17 shows the progression of the operation time ratio τ_{op} over the workload of the first machine f_1 for a segregated manufacturing systems consisting of two and three machines to be replaced by an integrated manufacturing system. For the system of three machines it is assumed that the remaining workload is shared evenly between the second and third machine. Furthermore, the impact of transportation time between the machines of the segregated system may be studied through the transportation time ratio $\tau_{tr,SMS}$.

Under all circumstances the operation time ratio τ_{op} required for smaller throughput times on the integrated system is minimal for an even workload distribution between the machines of the segregated manufacturing systems, see $\tau_{op,min}$ in figure 6.17. Definitely, the even distribution of workload depends on the number of machine tools and assumes a value of $f_1 = 50$ % for two machines and $f_1 = 33$ % for three machines.

The minimal operation time ratio $\tau_{op,min}$ depends on the transportation time ratio $\tau_{tr,SMS}$. If no transportation time is required to deliver the lots to the next machine within the segregated system, the operation time of the integrated manufacturing system $t_{op,IMS}$ must assume a value of $0{,}6 \cdot t_{op,SMS}$ in a system of two machines and $0{,}46 \cdot t_{op,SMS}$ in a system of three machines. However, if the transportation time ratio $\tau_{tr,SMS}$ assumes a value of four, operation times of the integrated system $t_{op,IMS}$ may even exceed operation times of the segregated system $t_{op,SMS}$ and yet the throughput times $t_{tp,IMS}$ are smaller than $t_{tp,SMS}$.

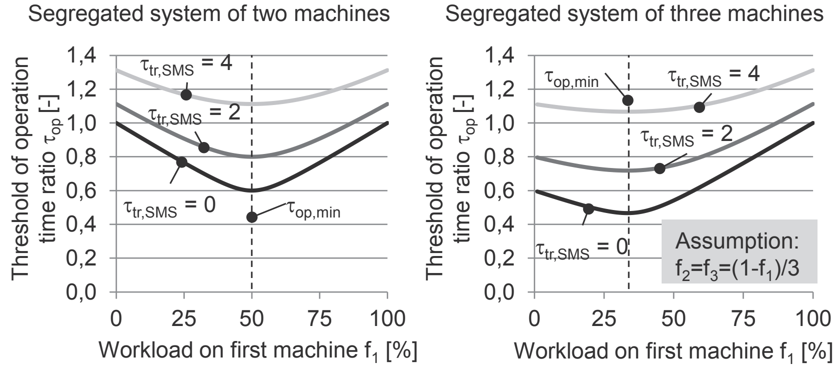


Figure 6.17: Operation time ratio for smaller throughput times

Verhältnis der Operationszeit für kleinere Durchlaufzeiten

The feasible operation time reduction depends on the effect of the workpiece change time reduction which varies over lot size m and workpiece complexity n as discussed in section 6.2.2. This effect is greatest in a domain of large lot sizes m and small workpiece complexity n, compare section 6.2.2. In this domain throughput times of the segregated manufacturing system will exceed throughput times of the integrated manufacturing system for relatively small transportation time ratios $\tau_{tr,SMS}$. Higher transportation time ratios $\tau_{tr,SMS}$ are required in a domain of small lot sizes m and large workpiece complexity n to assure that throughput times of the integrated manufacturing system undercut the throughput times of the segregated manufacturing system.

6.3 Synergy effects of manufacturing technology integration

The recent considerations of productivity, profitability, and throughput time allow for classifying synergy effects of manufacturing technology integration. A multi-technology platform represents a combination of the functional spectrum of at least two conventional single-technology machine tools. Depending on the type of manufacturing technologies to be combined and the workpiece spectra to be machined diverse synergy effects may or may not emerge.

According to the scheme depicted in figure 6.18 the functional synergy through manufacturing technology integration may create precision, monetary, and temporal synergy effects. These effects are linked to the elementary objectives of a manufacturing system, profitability and throughput time which account for the overall economic efficiency of manufacturing technology integration.

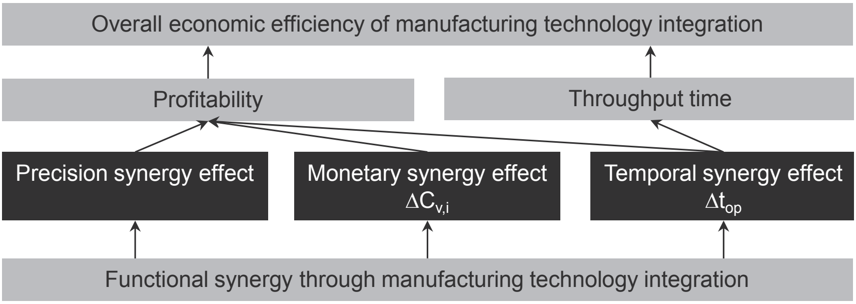


Figure 6.18: Classification of synergy effects of manufacturing technology integration
Klassifikation von Synergieeffekten von Fertigungstechnologieintegration

The precision synergy effect describes the enhancement of workpiece accuracy through manufacturing technology integration. Manufacturing technology integration may increase the precision because workpieces can be machined in a single clamping. Through this effect workpieces may be machinable on an integrated manufacturing system with a degree of accuracy that cannot be achieved by a serial chain of single-technology machine tools within the segregated manufacturing system.

The monetary synergy effect describes the difference in variable indirect cost of the integrated and the segregated manufacturing system consisting of the respective minimum number of system elements required to provide the same functional spectrum. This minimum number of system elements is a single multi-technology platform in case of manufacturing technology integration whereas a serial line of unparalleled single-technology machine tools is required in case of manufacturing technology integration.

$$\Delta C_{v,i} = C_{v,i,SMS}(x_{crit,SMS}) - c_{v,i,IMS} \tag{6.76}$$

The monetary synergy effect may be exploited in particular for low output quantities delimited by the critical output of a single multi-technology platform $x_{crit,IMS}$. Here the functional synergy between a serial line of single-technology machine tools and a single multi-technology platform is greatest. This is because e.g. a single machine bed or a single machine control is required in case of manufacturing technology integration whereas multiple machine beds and controls are necessary to operate the functions of the segregated manufacturing system. Hence, manufacturing technology integration should be considered in particular for low output quantities to take advantage of the monetary synergy effect.

The magnitude of monetary synergy effects depends on the degree of functional synergy which may be exploited through machine tool design. This aspect will be elucidated further in section 6.4.2.

The temporal synergy effect describes the reduction of operation time feasible through means of manufacturing technology integration. For single workspace multi-technology platforms the temporal synergy effect may be measured by the difference between the operation time of the segregated manufacturing system $t_{op,SMS}$ and the operation time of the integrated manufacturing system $t_{op,IMS}$:

$$\Delta t_{op} = t_{op,SMS} - t_{op,IMS} \tag{6.77}$$

The temporal synergy effect determines the relative productivity of a multi-technology platform in comparison to a serial chain of unparalleled single-technology machine tools. For single workspace multi-technology platforms the temporal synergy effect is most likely based on a workpiece change time reduction.

The condition of relative profitability for high output quantities comprises the quantities which determine the temporal and the monetary synergy effects, see expression (6.70) and (6.36). Hence, the relative profitability of manufacturing technology integration for high output quantities stipulates the interplay of the temporal and the monetary synergy effect of manufacturing technology integration.

6.4 Implications for the design of single workspace multi-technology platforms

The goal of the present chapter is to discuss the implications of production and cost theory for the design of multi-technology platforms. The design parameters under study are the number and the type of manufacturing technologies to be integrated.

6.4.1 Number of manufacturing technologies to be integrated

The dependency of the variable indirect cost threshold $\chi_{v,i,IMS}$ on the number of manufacturing technologies to be integrated will be discussed for low output quantities ($x < x_{crit,IMS}$) and high output quantities ($x \to \infty$). It will be assumed that the variable indirect costs of the single-technology machine tools of the segregated manufacturing system $c_{v,i,SMS,l}$ are equal at all stages of the transformation process to simplify the considerations:

$$\text{Assumption: } c_{v,i,SMS,l} = c_{v,i,SMS} \ \forall l \in \left[1,\ldots,L_{serial,SMS}\right] \tag{6.78}$$

This assumption is required to obtain a demonstrative conclusion about the feasibility of manufacturing technology integration with single workspace multi-technology platforms for low and high output quantities.

Low output quantities ($x < x_{crit,IMS}$)

At low output quantities a segregated manufacturing system in serial configuration may be substituted by a single multi-technology platform, see figure 6.19. By definition the number of manufacturing technologies ξ of the segregated manufacturing system are equal to the number of serial single-technology machine tools $L_{serial,SMS}$.

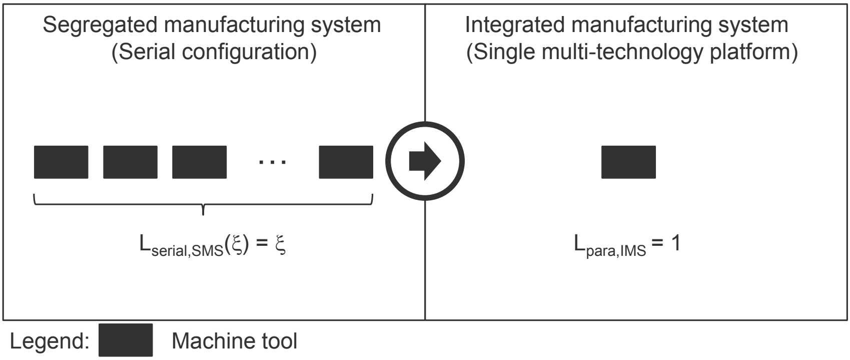


Figure 6.19: Manufacturing technology integration at low output quantities
Fertigungstechnologieintegration bei kleinen Stückzahlen

For low output quantities the condition of relative profitability of manufacturing technology integration is given by expression (6.68):

$$c_{v,i,IMS} < \chi_{v,i,IMS}(x < x_{crit,IMS}) = \sum_{l=1}^{L_{serial,SMS}} c_{v,i,SMS,l} \tag{6.79}$$

If expression (6.78) is applied the condition of relative profitability of manufacturing technology may be simplified as follows.

$$c_{v,i,IMS} < \chi_{v,i,IMS}(x < x_{crit,IMS}) = c_{v,i,SMS} \cdot \xi \tag{6.80}$$

The variable indirect cost threshold $\chi_{v,i,IMS}$ *grows linearly* over the number of manufacturing technologies to be integrated at low output quantities.

High output quantities ($x \rightarrow \infty$)

For high output quantities the parallelisation of machine tools within the integrated and the segregated manufacturing system needs to be considered as well, see figure 6.20.

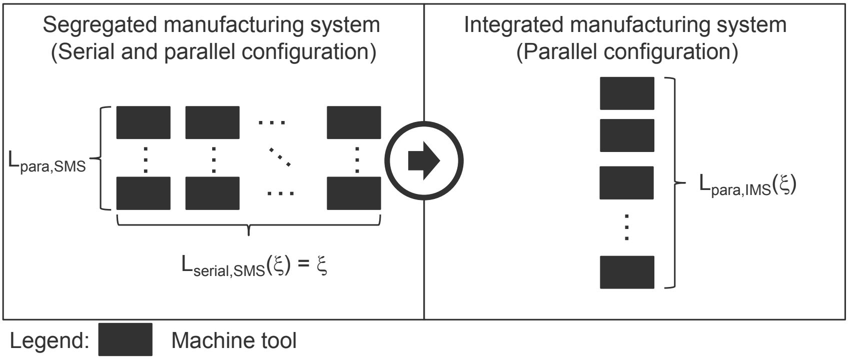


Figure 6.20: Manufacturing technology integration at high output quantities
Fertigungstechnologieintegration bei großen Stückzahlen

For high output quantities the condition of relative profitability of manufacturing technology integration is represented by expression (6.70) :

$$c_{v,i,IMS} < \chi_{v,i,IMS}(x \rightarrow \infty) = x_{crit,IMS} \cdot \sum_{l=1}^{L_{serial,SMS}} \frac{c_{v,i,SMS,l}}{x_{crit,l}} \tag{6.81}$$

The expression may be simplified by the following considerations. The critical output of the integrated manufacturing system is defined by the maximum operation time $\widehat{T}_{op}$ and the operation time $t_{op,IMS}$:

$$x_{crit,IMS} = \frac{\widehat{T}_{op}}{t_{op,IMS}} \tag{6.82}$$

To determine the critical output of a single-technology machine tool within the segregated manufacturing system the respective workload f_l needs to be taken into account as well:

$$x_{crit,l} = \frac{\widehat{T}_{op}}{t_{op,SMS} \cdot f_l} \tag{6.83}$$

The integrated manufacturing system may reach the highest market penetration if its variable indirect cost $c_{v,i,IMS}$ undercuts the cost threshold $\chi_{v,i,IMS}(x \rightarrow \infty)$ in case no temporal synergy effect prevails. If no temporal synergy effect exists the operation time of the integrated manufacturing system $t_{op,IMS}$ is equal to the operation time of the segregated manufacturing system $t_{op,SMS}$:

$$\Delta t_{op} = 0 \Leftrightarrow t_{op,IMS} = t_{op,SMS} \tag{6.84}$$

If expressions (6.78), (6.82), and (6.83) are applied, expression (6.81) may be simplified as follows:

$$c_{v,i,IMS} < \chi_{v,i,IMS}(x \rightarrow \infty) = c_{v,i,SMS} \cdot \overbrace{\frac{t_{op,SMS}}{t_{op,IMS}}}^{=1} \cdot \overbrace{\sum_{l=1}^{L_{serial,SMS}} f_l}^{=1} \tag{6.85}$$

The variable indirect cost threshold $\chi_{v,i,IMS}$ remains constant over the number of manufacturing technology to be integrated.

Now, the focus will be put on the progression of the variable indirect cost of a single multi-technology platform $c_{v,i,IMS}$ over the number of manufacturing technologies to be integrated. The left side of figure 6.21 shows that the execution of manufacturing technologies stipulates equipping a machine tool with an adequate functional spectrum. Typical functions required for the execution of manufacturing technologies are the linear feeding motions of the axes or the rotation of the tool. Furthermore, design elements provide the functions e.g. the drives feed the axes or the spindle rotates the tool.

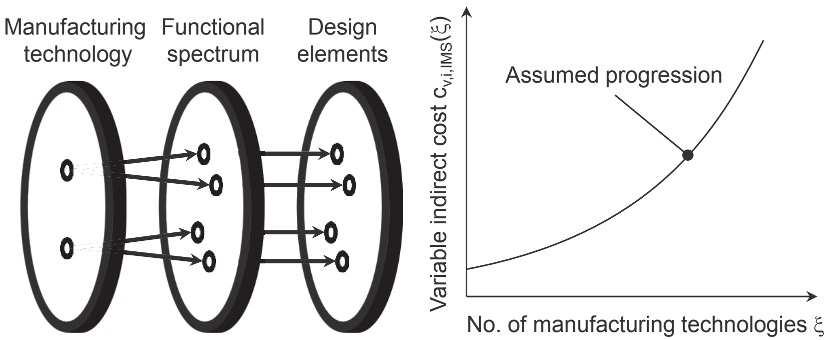


Figure 6.21: Progression of variable indirect cost over no. of manufacturing technologies
Verlauf der var. indirekten Kosten über der Anz. an Fertigungstechnologien

A multi-technology platform combines the functional spectrum of at least two manufacturing technologies. All design elements required for the execution of each manufacturing technology must be included into the structure of the machine tool. Hence, it seems reasonable to assume that the complexity of machine tool design and operation and as such the variable indirect cost $c_{v,i,IMS}$ increase progressively over the number of manufacturing technologies ξ to be integrated, see right side of figure 6.21. However, other assumptions about the progression of the variable indirect cost increase over the number of manufacturing technologies to be integrated would also be possible and may be discussed by the similar scheme that is presented in the following.

Figure 6.22 depicts the assumed progression of variable indirect cost $c_{v,i,IMS}$ and the progressions of the two thresholds for variable indirect cost, $\chi_{v,i,IMS}(x < x_{crit,IMS})$ and $\chi_{v,i,IMS}(x \rightarrow \infty)$, over the number of manufacturing technologies to be integrated ξ. In region 1 integrated manufacturing systems may reach some market penetration since variable indirect cost $c_{v,i,IMS}$ are smaller than the variable indirect cost threshold $\chi_{v,i,IMS}(x < x_{crit})$. However, the market access is limited to applications which require the manufacture of low output quantities.

$$\text{Region 1: } c_{v,i,IMS} < \chi_{v,i,IMS}(x < x_{crit,IMS}) = c_{v,i,SMS} \cdot \xi \tag{6.86}$$

If the variable indirect cost $c_{v,i,IMS}$ are higher than the variable indirect cost threshold for low output quantities $\chi_{v,i,IMS}(x < x_{crit,IMS})$ the respective integrated manufacturing system is too expensive to obtain any market penetration, see region 2 in figure 6.22

$$\text{Region 2: } c_{v,i,IMS} > \chi_{v,i,IMS}(x < x_{crit,IMS}) = c_{v,i,SMS} \cdot \xi \tag{6.87}$$

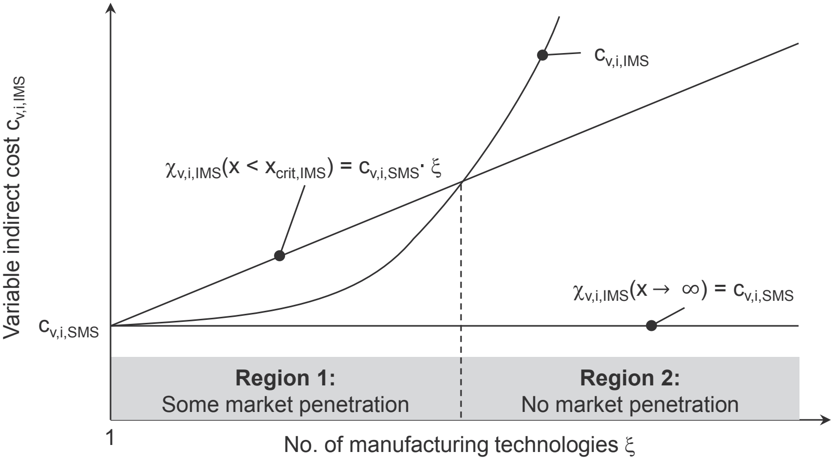


Figure 6.22: Relation between number of manuf. technologies and market penetration
Zusammenhang zwischen der Anzahl an FT und der Marktdurchdringung

Broad market penetration of integrated manufacturing systems stipulate variable indirect costs $c_{v,i,IMS}$ smaller than the variable indirect cost of a single-technology machine tool $c_{v,i,SMS}$, compare (6.88). However, the complexity of a multi-technology platform is higher than the complexity of a single-technology machine tool and thus the variable indirect cost of a multi-technology platform $c_{v,i,IMS}$ exceeds the variable indirect cost of a single-technology machine tool $c_{v,i,SMS}$, compare (6.89). This contradiction will be called the *paradoxon of manufacturing technology integration*.

$$c_{v,i,IMS} < \chi_{v,i,IMS}(x \rightarrow \infty) = c_{v,i,SMS} \tag{6.88}$$

$$c_{v,i,IMS} > c_{v,i,SMS} \tag{6.89}$$

The paradoxon illustrates that manufacturing technology integration with single workspace multi-technology platforms cannot be efficient in comparison to manufacturing technology segregation per se. If the functional spectrum of an entire process chain is integrated into a single multi-technology platform the maximum operation time T_{op} of the platform does not increase accordingly. Paradoxically, more and more processes need to be executed sequentially which increases the operation time per workpiece on the multi-technology platform $t_{op,IMS}$. Hence, the availability of each manufacturing technology is reduced if more manufacturing technologies are integrated. In consequence, multi-technology platforms need to be paralleled such that the integrated manufacturing system as a whole provides the required availability of each manufacturing technology. This, however, increases the variable indirect costs of the integrated manufacturing system.

Now, the question should be reflected by what means the additional cost for equipping a multi-technology platform with an enhanced functional spectrum can be reduced to a minimum through means of manufacturing technology integration. This leads to the question which type of manufacturing technologies should be combined on a multi-technology platform.

6.4.2 Type of manufacturing technologies to be integrated

The type of manufacturing technologies to be integrated will be discussed based on the monetary synergy effect of manufacturing technology integration. In section 6.3 the monetary synergy effect of manufacturing technology integration was introduced as the difference between the variable indirect cost of a serial line of unparalleled machine tools within the segregated manufacturing system $C_{v,i,SMS}$ and the variable indirect cost of a multi-technology platform $c_{v,i,IMS}$:

$$\Delta C_{v,i} = C_{v,i,SMS}(x_{crit,SMS}) - c_{v,i,IMS} \tag{6.90}$$

The monetary synergy effect results from functional synergy created if the functional spectrum of a serial line of single-technology machine tools is integrated into a multi-technology platform. However, depending on the type of manufacturing technologies to be integrated and the actual design of the machine tool synergy effects may or may not emerge. To elaborate further on monetary synergy effects of manufacturing technology integration, direct and indirect functions of the segregated manufacturing system will be distinguished.

Direct functions provided by direct design elements are required to create the relative movement between the workpiece and the tool in order to execute the respective manufacturing processes. The feed drives, the spindle, and the axes of a machine tool are examples for direct design elements. As opposed to direct functions, indirect functions only play an indirect role within the manufacturing process. Such indirect functions are provided by indirect design elements like machine tool controls or machine beds, but also operators may assume indirect functions within a manufacturing system. Hence, the variable indirect cost $c_{v,i,IMS}$ may split up into variable indirect cost related to direct functions (DF) $c^{DF}_{v,i,IMS}$ and variable indirect cost related to indirect functions (IF) $c^{IF}_{v,i,IMS}$:

$$c_{v,i,IMS} = c^{DF}_{v,i,IMS} + c^{IF}_{v,i,IMS} \tag{6.91}$$

Indirect functional synergy is created through elimination of indirect elements of the manufacturing system by means of manufacturing technology integration. In contrast to the serial line of single-technology machine tools within the segregated manufacturing system a multi-technology platform requires only a single machine control, a single machine bed, and a single operator (or a fraction of his workforce). Ideally, the variable indirect cost related to indirect functions of a multi-technology platform $c^{IF}_{v,i,IMS}$ remains constant over the number of manufacturing technologies to be integrated ξ and is equal to the variable indirect cost related to indirect functions of a single-technology machine tool within the segregated manufacturing system $c^{IF}_{v,i,IMS}$. As such the variable indirect cost related to indirect functions of a multi-technology platform $c^{IF}_{v,i,IMS}$ may fulfil the efficiency condition for high output quantities depicted in expression (6.88):

$$c^{IF}_{v,i,IMS} \geq c^{IF}_{v,i,SMS} \tag{6.92}$$

Direct functional synergy may exist between manufacturing technologies if the respective sets of required functionalities intersect partly. In this case the number of direct design elements required to enable the execution of an additional manufacturing technology may be reduced through a modular machine tool design. Two examples of direct functional synergy between two manufacturing technologies are depicted in figure 6.23 and figure 6.24.

Figure 6.23 shows the intersections between the functional sets of turning and roller burnishing. The execution of either technology stipulates a rotating workpiece, an axial feed, and a force intake. The design elements installed on a conventional turning machine may also be applied to execute a roller burnishing process. For this, the adapter of the roller burnishing tool is adjusted to the tool clamping unit of the respective turning machine. In fact, it is common in industry to carry out roller burnishing processes on turning machines rather than devoting an individual single-technology machine tool to roller burnishing.

Figure 6.24 depicts the intersections between the functional sets of a face milling and a drilling process. Either process requires a rotatory movement of the tool, a z-axis force intake, and a z-axis feeding motion. Additionally, the execution of a face milling process stipulates a x-/y-axis feeding motion and a x-/y-axis force intake. The functional synergy between drilling and face milling are used in machining centres that are equipped with a tool change unit that may clamp both, milling tools and drills.

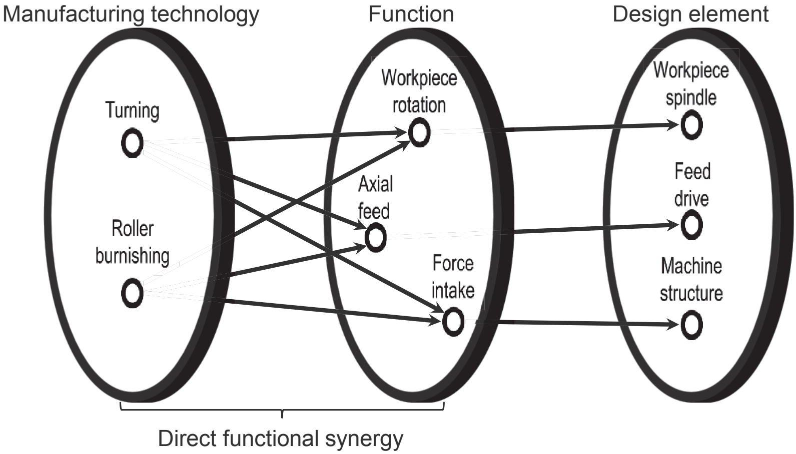


Figure 6.23: Functional synergy between turning and roller burnishing
Funktionale Synergie zwischen Drehen und Hartglattwalzen

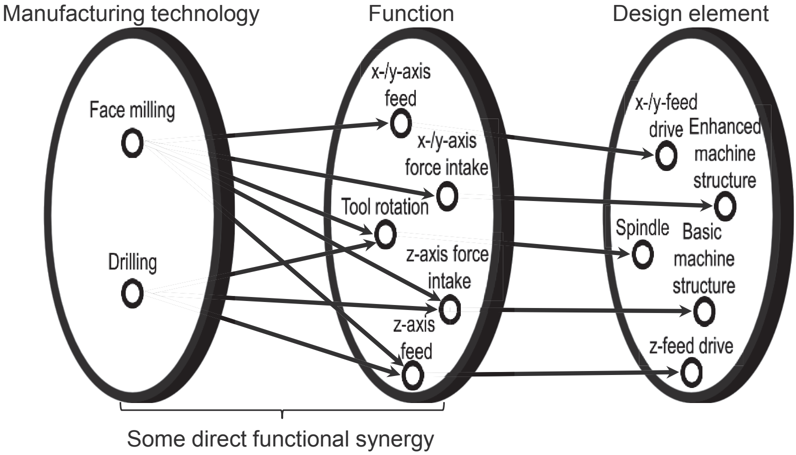


Figure 6.24: Functional synergy between face milling and drilling
Funktionale Synergie zwischen Fräsen und Bohren

Inevitably, the magnitude of functional synergy between manufacturing technologies exploitable by machine tool design depends on the type of manufacturing technologies to be integrated. If huge functional intersections prevail, the variable indirect cost increase related to the direct functions of an additional manufacturing technology may be less pronounced than in case of small functional synergy. However, it may be hypothesized that adding the functional spectrum of an additional manufacturing technology to a multi-technology platform always creates some increase of the variable indirect cost related to direct functions $c^{DF}_{v,i,IMS}$. As a consequence of such reasoning, the variable indirect cost of related to direct functions of a multi-technology platform $c^{DF}_{v,i,IMS}$ is always higher than the variable indirect cost related to direct functions of a single-technology machine tool $c^{DF}_{v,i,SMS}$:

$$c^{DF}_{v,i,IMS} > c^{DF}_{v,i,SMS} \tag{6.93}$$

Figure 6.25 compares the progressions of variable indirect cost $c_{v,i,IMS}$ over the number of manufacturing technologies in case functional synergy is exploitable to the case in which no functional synergy is exploitable. If functional synergy exists, a less pronounced variable indirect cost increase prevails over the number of manufacturing technologies. This signifies that more manufacturing technologies may be integrated and multi-technology platforms may reach a higher market penetration in case functional synergy is exploitable between the manufacturing technologies.

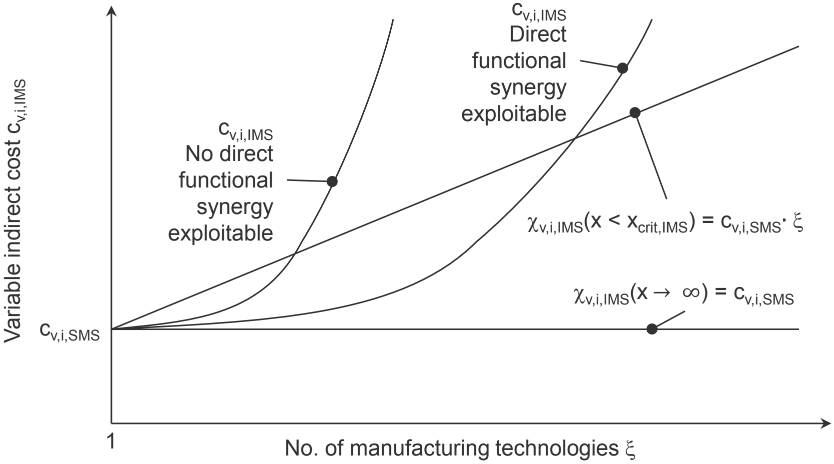


Figure 6.25: Effect of functional synergy on variable indirect cost progression

Effekt funktionaler Synergie auf den Verlauf variabler indirekter Kosten

However, the distinction criterion of manufacturing technologies per se is their functional dissimilarity. Hence, direct functional synergy between manufacturing technologies like turning and roller burnishing may be regarded an exception rather than a phenomenon that is expectable to exist between any arbitrary manufacturing technologies. In consequence, depending on the degree of functional synergy only few combinations of manufacturing technologies may reach broad market penetration in single workspace multi-technology platforms.

6.4.3 Motivation for sequential machining in double workspace MTP

Integrated manufacturing systems may compete successfully with segregated manufacturing systems in a domain of high output quantities if the variable indirect cost of a multi-technology platform $c_{v,i,IMS}$ is smaller than the variable indirect cost threshold for high output quantities $\chi_{v,i,IMS}(x \rightarrow \infty)$, see expression (6.85).

$$c_{v,i,IMS} < \chi_{v,i,IMS}(x \to \infty) = c_{v,i,SMS} \cdot \overbrace{\frac{t_{op,SMS}}{t_{op,IMS}}}^{=1/\tau_{op}} \cdot \overbrace{\sum_{l=1}^{L_{serial,SMS}} f_l}^{=1} \tag{6.94}$$

The cost threshold $\chi_{v,i,IMS}$ depends on the ratio of operation time τ_{op}, which is a measure for the temporal synergy effect of manufacturing technology integration. The considerations in section 6.2.2 have shown that the temporal synergy effect for single workspace multi-technology platforms is based on a reduction of workpiece change time. Hence, the magnitude of the temporal synergy effect depends on the choice of workpiece spectrum to be machined on the single workspace multi-technology platform. If no temporal synergy effect prevails for the considered workpiece spectrum, the variable indirect cost of a multi-technology platform $c_{v,i,IMS}$ must be smaller than the variable indirect cost of a single-technology machine tool which was considered impossible (paradoxon of manufacturing technology integration). Hence, it would be desirable to generate a temporal synergy effect of manufacturing technology integration by another mechanism than solely a workpiece change time reduction to broaden the applicability of integrated manufacturing systems.

The productivity of integrated manufacturing systems may be enhanced in comparison to segregated manufacturing systems through equipping multi-technology platforms with two workspaces. According to figure 3.3 two distinct kinds of double workspace multi-technology platforms may be distinguished. Either double workspace multi-technology platforms pass the workpieces between the workspaces (sequential machining) or the technology resources travel between the workspaces (parallel machining), the latter will be addressed in chapter 7. The following considerations clarify the motivation of double workspace multi-technology platforms for sequential processing.

If the workpieces are passed between the workspaces only a part of the workload is carried by each workspace. In case no other temporal synergy effect prevails, the operation time of the bottleneck workspace $t_{op,IMS}$ is equal to the operation time of the segregated manufacturing system $t_{op,SMS}$ multiplied by the maximum workload fraction $f_{IMS,max}$.

$$t_{op,IMS} = t_{op,SMS} \cdot f_{IMS,max} \tag{6.95}$$

However, the additional workspace and the additional technology resources installed increase the variable indirect cost of the integrated manufacturing system $c_{v,i,IMS}$ by $\Delta c_{v,i,IMS}$. Hence, the effectiveness of equipping a multi-technology platform with a second workspace for sequential machining must be determined by the following expression:

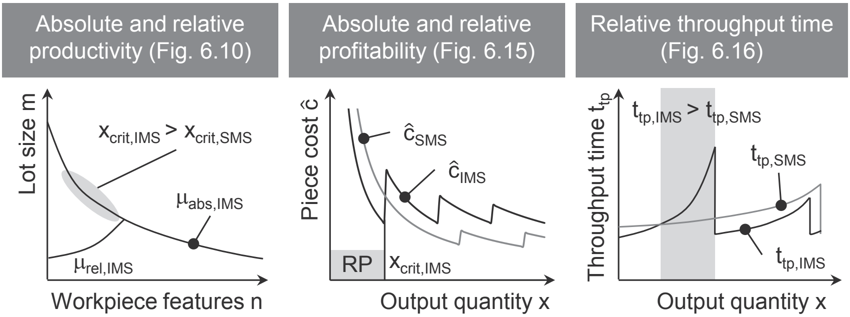
$$c_{v,i,IMS} + \Delta c_{v,i,IMS} < \chi_{v,i,IMS}(x \rightarrow \infty) = c_{v,i,SMS} \cdot f_{IMS,max} \qquad (6.96)$$

6.5 Interim conclusion

In chapter 6 production, cost, and queuing theory were applied to study the economic efficiency of single workspace multi-technology platforms. The results clearly indicate that economic efficiency of integrated manufacturing systems exists only under certain boundary conditions. Thus, manufacturing technology integration and segregation are machine tool and manufacturing system design paradigms which will exist in parallel in the future.

Figure 6.26 summarizes the key findings of section 6.2 “Derivation of efficiency conditions”. At its absolute productivity limit a multi-technology platform may either produce small lot sizes of complex workpieces or large lot sizes of simple workpieces. The relative productivity of an integrated manufacturing system in comparison to a segregated manufacturing system was studied to evaluate which of these options possesses a huger impact on productivity. It was argued that most likely manufacturing technology integration reduces the workpiece change times t_{wc} whereas the changeover times t_{co} and the processing times t_p are equal to or higher than those of the segregated manufacturing system. Smaller workpiece change times enhance the productivity of integrated manufacturing systems in comparison to segregated manufacturing systems, in particular, in a domain of small workpiece complexity and large lot sizes. However, it was concluded that most likely the absolute productivity of a multi-technology platform is smaller than the productivity of a serial chain of single-technology machine tools. This is because a multi-technology platform possesses a single workspace only whereas multiple workspaces exist within the segregated manufacturing system. Hence, multi-technology platforms must be paralleled such that an integrated manufacturing system provides the same productivity as a segregated manufacturing system.

Absolute profitability of integrated manufacturing systems stipulates the production of high value products. The parallelisation of multi-technology platforms must be considered to determine the critical value per workpiece which ensures a punctual transition of the value creation and the total cost function. Furthermore, the output must excel the break-even output quantity x_{be}. Relative profitability of manufacturing technology integration depends on the variable indirect costs of the integrated and the segregated manufacturing system. The condition of relative economic efficiency of manufacturing technology integration is less restrictive for low output quantities and an uneven workload distribution between the single-technology machine tools of the segregated manufacturing system. Hence, output quantities smaller than the productivity limit of a multi-technology platform and an uneven workload distribution are desirable if manufacturing technology integration is considered.



Key findings

Productivity higher for
- large lot size m
- small number of workpiece features n

Profitability higher for
- low output quantities beneath $x_{crit,IMS}$
- beyond break-even output quantity $x_{be,IMS}$

Throughput times
- Logistic chain of IMS shorter
- Throughput times may be higher

Figure 6.26: Key findings of section 5.2
Hauptergebnisse von Kapitel 5.2

The study of relative throughput times revealed that the shortening of the logistic chain through manufacturing technology integration does not necessarily account for smaller throughput times. Throughput times may be reduced if the ratio between operation times of the integrated and the segregated manufacturing systems undercuts a critical value which depends on the transportation times within the segregated manufacturing system.

In the last section the implications of production and cost theory for the design of single workspace multi-technology platforms were discussed. It was assumed that the variable indirect cost of a multi-technology platform increases progressively over the number of integrated manufacturing technologies. Integrated manufacturing systems may reach some market penetration if the variable indirect costs are smaller than the variable indirect cost threshold for low output quantities $\chi_{v,i,IMS}(x<x_{crit,IMS})$. Broad market penetration would be feasible if the variable indirect cost of a multi-technology platform $c_{v,i,IMS}$ were smaller than the variable indirect cost of a single-technology machine tool $c_{v,i,SMS}$. However, due to the larger complexity of the multi-technology platform this was considered infeasible (paradoxon of manufacturing technology integration). Furthermore, direct and indirect functional synergy may exist between the single-technology machine tools of a segregated manufacturing system. Direct functional synergy prevails if the functional sets of two manufacturing technologies intersect partly. In this case, the number of design elements required to execute the manufacturing technologies may be reduced which increases the competitiveness of the respective multi-technology platform.

7 Economic efficiency of double workspace MTP

The motivation of equipping a multi-technology platform with a second workspace and allowing the technology resources to travel between the workspaces (parallel machining) originates in the deficits of multi-technology platforms with a single workspace. Chapter 6.3 has shown that relative economic profitability of single workspace multi-technology platforms stipulates the interplay of monetary and temporal synergy effects. Monetary synergy effects are highest if direct functional synergy between the individual manufacturing technologies may be exploited by machine tool design, see section 6.4.2. Furthermore, a significant reduction of workpiece change time may create a temporal synergy effect that reduces the number of paralleled multi-technology platforms $L_{para,IMS}$ required to produce the desired output x.

Successively, it signifies that in case no significant reduction of workpiece change time is technically feasible relative profitability of manufacturing technology integration must be created solely by a huge monetary synergy effect. This would restrict the efficient application of integrated manufacturing systems with single workspace multi-technology platforms to few cases in which a huge monetary synergy effect prevails e.g. due to direct functional synergy between the manufacturing technologies. Hence, an alternative mechanism to create a temporal synergy effect apart from a workpiece change time reduction would be desirable to enhance the relative profitability of multi-technology platforms.

Seeking an alternative temporal synergy effect of manufacturing technology integration, the progression of workspace and technology resource utilization U of a multi-technology platform with a single workspace over the output x will be considered, see figure 7.1. The left side of the diagram depicts an even utilization and the right diagram an uneven utilization of the two installed manufacturing technologies per workpiece. In either case, the workspace utilization U_{ws} is twice as high as the average technology resource utilization U_{Tm}, because the technology resources alternate processing the workpiece. One technology resource is idle at all times. [BREC13]

To generate an additional temporal synergy effect of manufacturing technology integration Brecher suggests equipping a multi-technology platform with a second workspace and enabling the traveling of technology resources between the two workspaces [BREC08]. This approach may raise the average utilization of technology resources because the technology resource which is idle in one workspace may be applied in the respective other workspace. In consequence, due to the simultaneous processing of two workpieces the critical output of the multi-technology platform $x_{crit,IMS}$ increases as well. [BREC13]

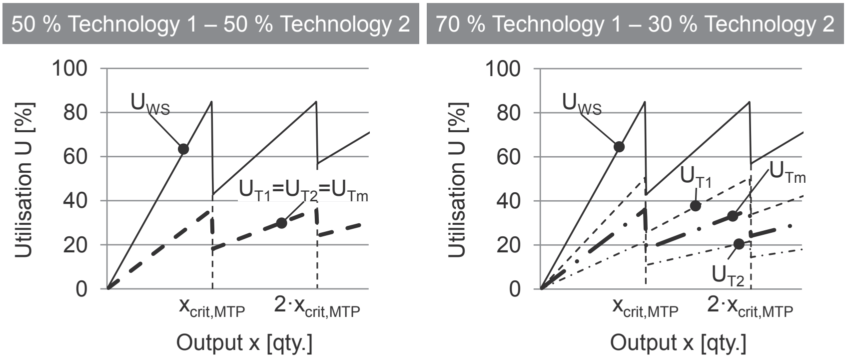


Figure 7.1: Utilization of technology resources in single workspace MTP
Nutzung der Technologieressourcen in MTP mit einem Arbeitsraum

The objective of this chapter is to extend the theory of economic efficiency of manufacturing technology integration to multi-technology platforms with two workspaces. The enhanced theory will allow for the quantitative consideration of the additional temporal synergy effects of manufacturing technology integration related to the second workspace in comparison to multi-technology platforms with a single workspace.

The structure of chapter 7 is equivalent to the structure of chapter 6 and follows Dyckhoff’s scheme to derive a special production theory [DYCK03, p. 713]. The extent of application and the implementation by the models of the structural core takes place in section 7.1. However, as opposed to the static-deterministic equations of classical production theory which were applied in section 6.1 it will be reasoned that dynamic-stochastic models are more suitable to describe the input-output relations of multi-technology platforms with two workspaces. Section 7.2 derives efficiency conditions with regard to relative productivity, relative profitability and relative throughput times of double workspace multi-technology platforms in comparison to single workspace multi-technology platforms and segregated manufacturing systems.

7.1 Extent of application and model implementation

Two distinct configurations of double workspace multi-technology platforms will be considered and compared to a single workspace multi-technology platforms with two technology resources, see figure 7.2. Configuration 1 is characterized by two distinct technology resources which may travel between the workspaces. This configuration refers to the double workspace multi-technology platform “Chiron M 2000” presented by Brecher et al. [BREC08; BREC12a; BREC13]. The Chiron M 2000 is equipped with a milling and a laser welding/ structuring head. Configuration 2 comprises three technology resources. Each workspace possesses an individual technology resource 1 for example one milling head is installed in either workspace. Only technology resource 2 may travel between the workspaces.

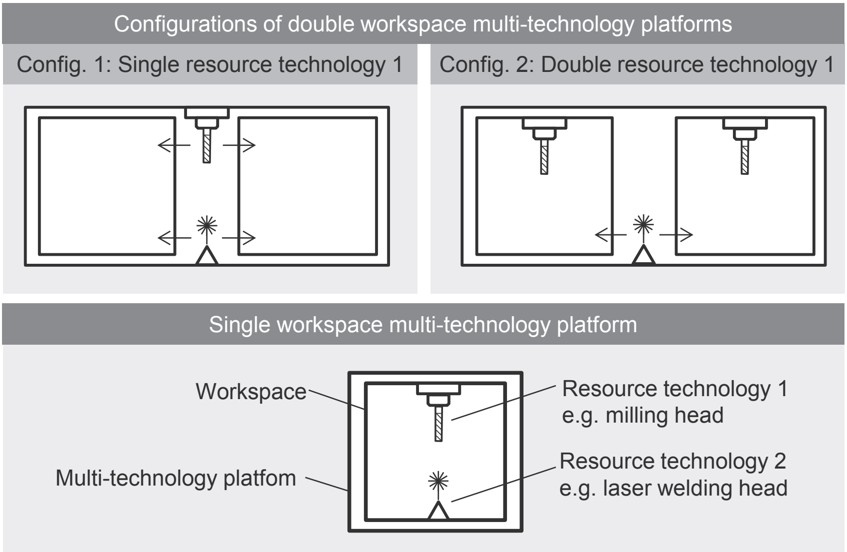


Figure 7.2: Considered configurations of double workspace MTPs

Betrachtete Konfigurationen von MTPs mit zwei Arbeitsräumen

The model implementation follows the structure of section 6.1. First, input-output relations are described by a production function in section 7.1.1. Subsequently, the production function is linked to a profitability function (section 7.1.2) and a throughput time function (section 7.1.3).

7.1.1 Production function

As emphasised in section 6.1.1 the Gutenberg production function which is applied in this thesis to describe the input-output relations of the manufacturing systems under study consists of a potential and a consumption function. While the outline of the consumption function introduced in the previous chapter may be transferred to double workspace multi-technology platforms the potential function must be capable of describing rule-based workspace interactions which will be discussed in the following.

Such workspace interactions are illustrated by the exemplary throughput diagram of a double workspace multi-technology platform (configuration 1) in figure 7.3. The i-th and the j-th order arrive simultaneously at workspace 1 and workspace 2 of the multi-technology platform. Both workspaces are occupied by previous orders in the moment of order arrival. This causes waiting time before the workspaces may be changed over to allow for the processing of the newly arrived orders. After changeover both orders demand technology resource 1. Since the i-th order occupies technology resource 1 at first in workspace 1 the processing of the j-th order in workspace 2 is interrupted until technology resource 1 is vacant. In other words, the first interaction between workspace 1 and workspace 2 takes place based on the rule that the two workspaces may not apply the same technology resource simultaneously. Subsequently, technology resource 2 may be applied instantly in workspace 1. However, the second execution of the process with technology resource 1 starts with a delay as the technology resource is still occupied in workspace 1 (2. workspace interaction). As soon as all processing steps of either order are completed the i+1-th and the j+1-th order may enter the respective workspace.

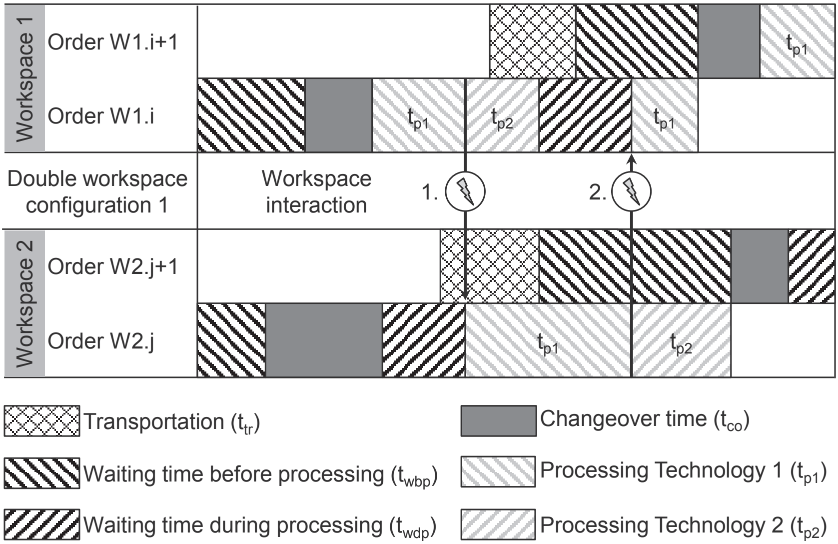


Figure 7.3: Throughput diagram: Interaction between workspace 1 and 2
Durchlaufdiagram: Wechselwirkung zwischen Arbeitsraum 1 und 2

The rule-based workspace interactions illustrated by figure 7.3 may not be modelled by classical static-deterministic production theory but by simulations based on dynamic-stochastic funnel models, compare [WIEN10, p. 15]. The concept of funnel models and discrete-event simulation models were taken from literature and adapted by the author for single and double workspace multi-technology platforms of configuration 1 and 2. The simulations of double workspace multi-technology platforms presented in this thesis were realised by computer programs in MATLAB ® , see appendix 12.2. For the first time the rule-based workspace interactions of double workspace multi-technology platforms were mapped by a discrete-simulation modelling approach.

The fundamental idea of funnel models is depicted on the left side of figure 7.4. Orders queue separately in front of workspace 1 and workspace 2. Processing step by processing step the program checks whether the respective technology resource required is available and whether the machining of a workpiece or an order has been completed etc. Definitely, the program of configuration 1 differs from the program of configuration 2 in the sense that in case of configuration 2 technology resource 1 is always available whereas the limited availability of technology resource 1 may cause waiting times in case of configuration 1.

Two distinct workpiece feeding modes were applied to determine the productivity boundaries of double workspace multi-technology platforms, see right side in figure 7.4. In the most straightforward feeding mode workpieces of similar properties arrive at workspace 1 and workspace 2. The likelihood of utilizing technology resource 1 and 2 is equally high for either workspace. However, this feeding mode leads to a similar utilization of technology resource 1 and technology resource 2, which may reduce the productivity of a double workspace multi-technology platform. Hence, Brecher and Breitbach suggested considering measures to optimize the “use of simultaneous processing with two workspaces” by alternative workpiece feeding modes [BREC13]. The maximum potential of such approaches is reflected by the most extreme feeding mode, that is, feeding workpieces with complementary properties. In this mode the likelihood of utilizing technology resource 1 in workspace 1 is equal to the likelihood of utilizing technology resource 2 in workspace 2.

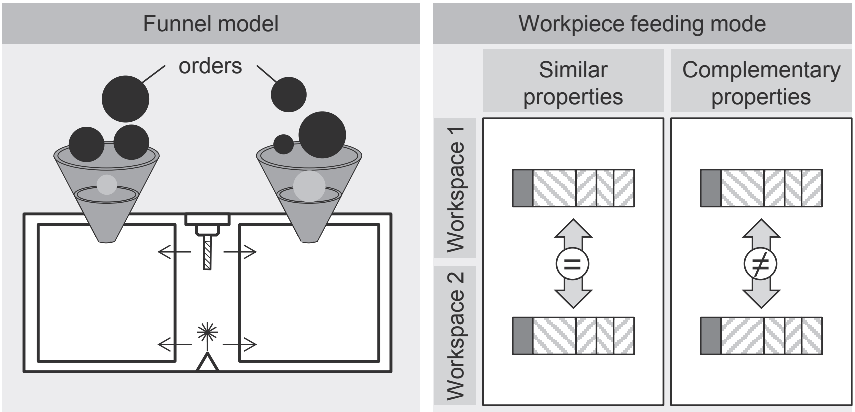


Figure 7.4: Funnel model and workpiece feeding modes
Trichtermodell und Werkstückzufuhrarten

In the following the machining of diverse workpiece spectra was simulated to enable the comparison of productivity of single and double workspace multi-technology platforms of configuration 1 and 2. Depending on the workpiece feeding mode the properties of the workpiece spectra for each workspace were altered stochastically. It was assumed that each workpiece spectrum consisted of five workpiece types which were specified by normally distributed but non-negative numbers of processes n and processing times t_p. The respective stochastic distributions were characterised a priori by the mean and the standard deviation. Furthermore, the relative likelihood of technology resource utilization RL_{T1} and RL_{T2} determined a threshold, which was compared to an evenly distributed random number between zero and one generated for each process. If the number exceeded the threshold the second technology resource was assigned to the process. Otherwise, the process was considered to be executable by technology resource one.

Based on the workpiece spectrum consisting of five distinct workpiece types per workspace the generation of an order list took place for each simulation run. Besides the workspace the order list specified the time of order arrival based on the Poisson distributed birth rate of orders λ, the lot size m, and the changeover time t_{co}.

Two further rules were assumed in the simulation of order processing by double workspace multi-technology platforms. First, during the changeover of one workspace the respective other workspace may continue processing workpieces. The validity of this assumption depends on the manufacturing technologies and the safety measures installed e.g. if laser welding takes place in one workspace parallel changeover of the other workspace stipulates suitable optical encapsulation. Second, a pre-processing routine was applied to the randomly generated orders to merge all processes with similar technology resources that take place consecutively on a single workpiece. Hence, if similar processes were executed consecutively on the same workpiece in one workspace the respective technology resource was not allowed to carry out a process in the other workspace in between.

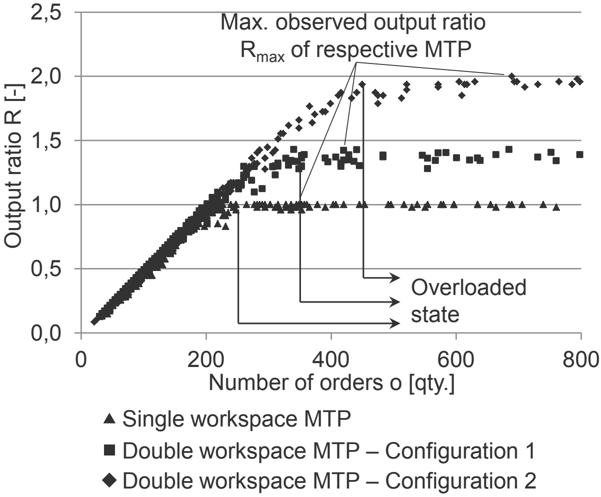
Figure 7.5 shows the result of several hundred simulation runs with all three considered multi-technology platforms defined by figure 7.2. The birth rate of orders λ and thus the number of orders o to be processed was increased stepwise until the respective multi-technology platforms were no longer capable of machining all orders during the simulation period T. Hence, at the maximum birth rate of orders λ_{max} all multi-technology platforms operated in the so-called overloaded state, compare [NYHU09, p. 36].

The overloaded state was chosen for the productivity comparison depicted in this chapter because of two reasons. First, in this state queues in front of multi-technology platforms grow beyond all limits. Hence, productivity losses due to idling were avoided. Second, the productivity comparison had to take place under similar boundary conditions in terms of throughput times. It was easier to conduct the productivity comparison for theoretically infinite throughput times than for any other value, because the model did not comprise a load-dependent order release mechanism, compare [NYHU09].

Subsequently, the maximum number of orders processed during the simulation period was determined for each multi-technology platform and related to the maximum number of orders processed by the single-workspace multi-technology platform. This ratio will be called maximum observed output ratio R_{max}. In terms of the static deterministic modelling approach of relative productivity in section 6.2.2 the ratio R_{max} describes the quotient of critical output of a double workspace multi-technology platform $x_{crit,2WS}$ and a single workspace multi-technology platform $x_{crit,1WS}$.

$$R_{max} = \frac{x_{crit,2WS}}{x_{crit,1WS}} \tag{7.1}$$

The characteristic R_{max} measures the additional temporal synergy effect as a result of equipping a multi-technology platform with a second workspace. Obviously, the ratio R_{max} assumed a value of one for the single workspace multi-technology platform while the ratio R_{max} exceeds one for the multi-technology platforms with two workspaces.



Lot size
m_{μ} = 5
Number of processes
n_{μ} = 4
Processing time
$t_{p,\mu}$ = 1 min
Changeover time
t_{co} = 1 min
Rel. likelihood T1
RL_{T1} = 80 %
Rel. likelihood T2
RL_{T2} = 20 %
Simulation period
T = 1000 min

Figure 7.5: Determination of maximum observed output ratio R_{max}

Bestimmung des maximalen Ausbringungsmengenverhältnisses R_{max}

7.1.2 Profitability function

In section 6.1.2 the profitability function of single workspace multi-technology platforms was introduced which comprises a value creation function and a cost function. The cost of an integrated manufacturing system consisting of double workspace multi-technology platforms may be described by the cost function of a single workspace multi-technology platform in expression (6.24).

A double workspace multi-technology platform enhances the productivity in comparison to a single workspace multi-technology platform. However, this productivity enhancement is linked to additional resources with are installed on double workspace multi-technology platforms. Apart from the second workspace the multi-technology platform of configuration 1 comprises two traveling units which enable technology resource 1 and 2 to enter each workspace. Hence, the additional cost for the second workspace $\Delta C_{sys,WS2}$ and the additional cost for the two traveling units $\Delta C_{sys,TU}$ must be considered to describe the system cost of a double workspace multi-technology platform of configuration 1 $C_{sys,Config\_2}$ in comparison to the system cost of a single workspace multi-technology platform $C_{sys,1WS}$ by the following model:

$$C_{sys,Config\_1} = C_{sys,1WS} + \Delta C_{sys,WS2} + 2 \cdot \Delta C_{sys,TU} \quad (7.2)$$

Instead of the second traveling unit the double workspace multi-technology platform of configuration 2 contains an additional technology resource 1, compare figure 7.2. This additional technology resource 1 raises the system costs by $\Delta C_{sys,TR}$, while the system cost of the traveling unit must only be considered only once:

$$C_{sys,Config\_2} = C_{sys,1WS} + \Delta C_{sys,WS2} + \Delta C_{sys,TU} + \Delta C_{sys,TR} \quad (7.3)$$

The system cost model will be applied in section 7.2.2 to discuss the propitiousness of a second technology resource 1 for configuration 2 in comparison to a second traveling unit for configuration 1.

7.1.3 Throughput time function

Section 7.1.1 outlined that classical production theory is hardly applicable to map the input-output relations of double workspace multi-technology platforms due to the dynamic-stochastic behaviour of workspace interactions. Based on this reasoning mathematical queuing theory introduced in section 6.1.3 must be rejected as well to describe throughput times of double workspace multi-technology platforms. This is, because those throughput times are largely determined by waiting times within the workspaces as a consequence of workspace interactions, compare section 7.1.1. Hence, instead of mathematical queuing theory, the study on throughput times of double workspace multi-technology platforms was conducted based on discrete-event simulation of funnel models, too.

In comparison to throughput times of a single workspace multi-technology platform the throughput time of a double workspace multi-technology platform comprises waiting times during processing as an additional term, compare figure 7.2. Thus expression (6.34) must be extended by the total waiting time during processing $t_{wdp,2WS}$:

$$t_{tp,2WS} = t_{tr,2WS} + t_{wbp,2WS} + t_{op,2WS} + t_{wdp,2WS} \quad (7.4)$$

The total waiting time during processing $t_{wdp,2WS}$ is equal to the sum of all waiting times between individual processes due to I workspace interactions.

$$t_{wdp} = \sum_{i=1}^{I} t_{wdp,i} \quad (7.5)$$

The throughput time model will be applied in section 7.2.3 to discuss the throughput time increase caused by workspace interactions in double workspace multi-technology platforms.

7.2 Derivation of efficiency conditions

Based on the model implementation depicted in section 7.1, the discussion on relative economic efficiency of manufacturing technology integration in double workspace multi-technology platforms may take place subsequently. For this, double workspace multi-technology platforms will be compared to an integrated manufacturing system consisting of a single workspace multi-technology platform. Like in section 6.2 the discussion on relative economic efficiency is conducted with regard to three efficiency criteria, productivity (section 7.2.1), profitability (section 7.2.2) and throughput time (section 7.2.3).

7.2.1 Relative productivity

In section 7.1.1 the method to determine the additional temporal synergy effect of a second workspace by the maximum output ratio R_{max} of a double workspace multi-technology platform in comparison to a single workspace multi-technology platform was introduced. The ratio R_{max} will now be studied with regard to the configuration of the double workspace multi-technology platform and the type of orders machined in a domain of similar and complementary workpiece feeding mode.

The impact of two order type properties on the productivity of the double workspace multi-technology platforms are of particular interest. Firstly, the relative likelihood of each technology during the machining of a workpiece influences the amount of workspace interaction that may occur. Secondly, the order properties favourable of taking advantage of the assumed ability of a double workspace multi-technology platform to change over one workspace while the other workspace is still machining workpieces are identified.

Similar workpiece feeding mode

Figure 7.6 depicts the impact of the relative likelihood of technology 1 on the maximum observed output ratio R_{max} for double workspace multi-technology platforms of configuration 1 and 2 in similar workpiece feeding mode. In similar workpiece feeding mode the relative likelihood of technology 1 during machining of workpieces is equal for both workspaces. Based on ten simulation runs the mean value of the maximum observed output ratio R_{max} was determined.

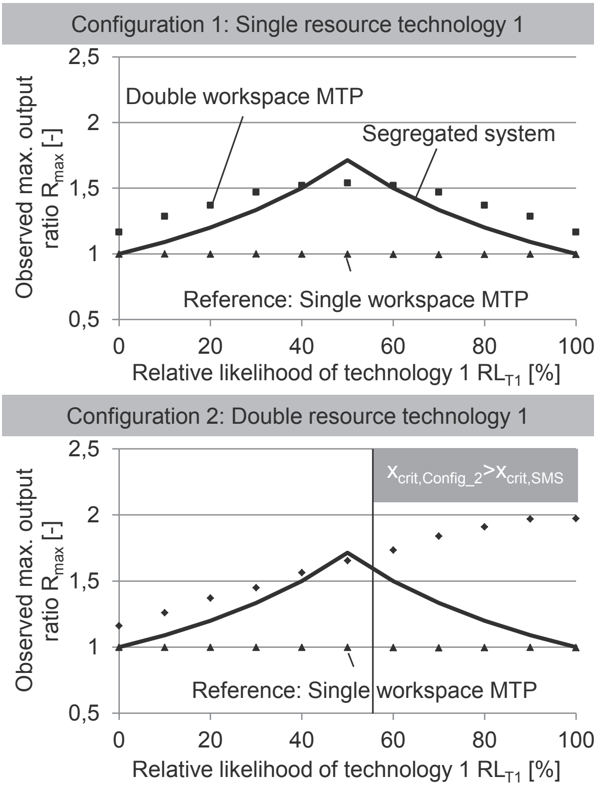
The double workspace multi-technology platform of configuration 1 was most productive for an equal relative likelihood of technology 1 and technology 2 during the machining of workpieces, see upper diagram in figure 7.6. At this point the output of the double workspace multi-technology platform assumed a value of 1,63 times the output of a single workspace multi-technology platform.

The maximum output ratio of a segregated manufacturing system consisting of two single-technology machine tools in comparison to a single workspace multi-technology platform $R_{max,SMS}$ may be estimated by the following expression:

$$R_{max,SMS} = \frac{x_{crit,SMS}}{x_{crit,1WS}} = \frac{t_{co} + m \cdot n \cdot t_p}{t_{co} + m \cdot n \cdot t_p \cdot \max(RL_{T1}, RL_{T2})} \qquad (7.6)$$

The productivity limit of the segregated manufacturing system possessed a similar progression over the relative likelihood of technology 1 than the double workspace multi-technology platform of configuration 1. Both manufacturing systems reached the maximum productivity for a relative likelihood of technology 1 of 50 %. No region existed in wich the productivity of the double workspace multi-technology platform of configuration 1 was significantly higher than the productivity of the segregated manufacturing system.

The positive effect of an individual technology resource 1 in either workspace (configuration 2) on productivity became significantly noticeable beyond a relative likelihood of technology 1 of 60 %, see lower diagram of figure 7.6. For relative likelihoods of technology 1 between 80 % and 100 %, the productivity of double workspace multi-technology platform of configuration 2 was almost twice as high as the productivity of a single workspace multi-technology platform. Beyond a relative likelihood of technology 1 of 60 % the productivity of the double workspace multi-technology platform of configuration 2 $x_{crit,Config\_2}$ exceeded the productivity of the segregated manufacturing system consisting of two machines significantly.



Simulation period
T = 2500 min

Simulation repetitions
SR = 10

Workpiece spectrum
N = 5

Lot size
m_μ = 5
m_σ = 1

Workiece complexity
n_μ = 10
n_σ = 2

Processing time
$t_{p,\mu}$ = 0,75 min
$t_{p,\sigma}$ = 0,25 min

Changeover time
t_{co} = 7,50 min

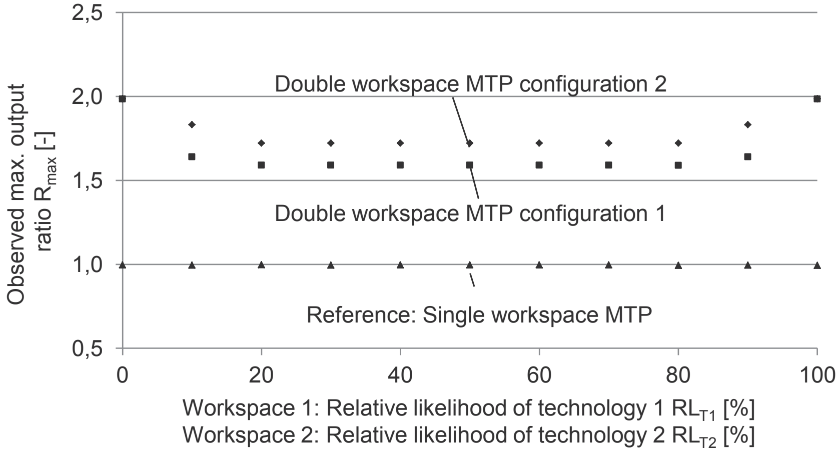
Relative likelihood technology 2
RL_{T2} = $1-RL_{T1}$

Figure 7.6: Productivity comparison for similar workpiece feeding mode
Produktivitätsvergleich für Zufuhr von gleichen Werkstücken

Furthermore, the productivity of either double workspace multi-technology platform exceeded the productivity of a single workspace multi-technology platform for a relative likelihood of technology 1 of 0 %. This observation is explainable by the enhancement of productivity due to the assumed ability to change over one workspace while the respective other workspace was still processing workpieces. A study of this enhancement of productivity through selection of the workpiece domain takes place after the discussion of the complementary workpiece feeding mode.

Complementary workpiece feeding mode

Figure 7.7 illustrates the magnitude of the additional temporal synergy effect of a second workspace in a domain of complementary workpiece feeding mode. In this domain the relative likelihood of technology 1 in workspace 1 is equal to the relative likelihood of technology 2 in workspace 2. Thus, the complementary workpiece feeding mode may be regarded as the most extreme case of productivity enhancement by feeding workpieces of distinct properties to the workspaces.



Simulation period
$T = 2500$ min
Simulation repetitions
$SR = 10$
Workpiece spectrum
$N = 5$
Lot size
$m_{\mu} = 5$
$m_{\sigma} = 1$

Workiece complexity
$n_{\mu} = 10$
$n_{\sigma} = 2$

Processing time
$t_{p,\mu} = 0{,}75$ min
$t_{p,\sigma} = 0{,}25$ min

Changeover time
$t_{co} = 7{,}50$ min

Workspace 1
$RL_{T2} = 1-RL_{T1}$

Workspace 2
$RL_{T1} = 1-RL_{T2}$

Figure 7.7: Productivity comparison for complementary workpiece feeding mode
Produktivitätsvergleich für Zufuhr von komplementären Werkstücken

Complementary workpiece feeding increased the relative productivity of the double workspace multi-technology platform of configuration 1 significantly in comparison to the similar workpiece feeding mode, see upper diagram in figure 7.7. Although, the double workspace multi-technology platform of configuration 2 was more productive than the double workspace multi-technology platform of configuration 1 a much smaller productivity gap between both alternative design options prevailed than in complementary workpiece feeding mode, compare figure 7.7.

However, the approach of complementary workpiece feeding only works with an adequate workpiece spectrum and huge effort is required to analyse the relative utilization frequencies of each technology resource a priori. Thus, it remains to be proven that such an approach is suitable for an industrial application.

Further enhancement of productivity through selection of workpiece domain

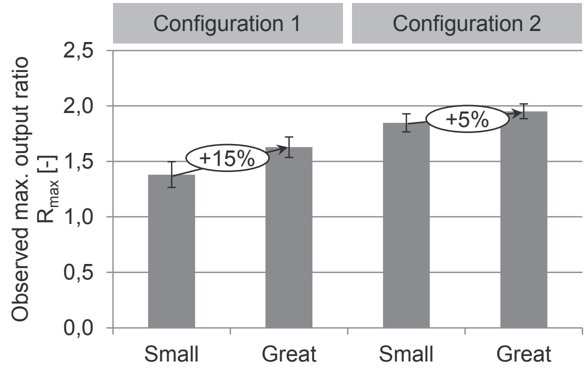
In section 6.2.2 the influence of a changeover time, a workpiece change time, and a processing time reduction on the temporal synergy effect of a single workspace multi-technology platform was studied through the characteristics, $\Delta\tau_{co}$, $\Delta\tau_{wc}$, and $\Delta\tau_{p}$. It was concluded that the temporal synergy effect of technology integration with a single workspace multi-technology platform most likely results from a significant workpiece change time reduction. This kind of temporal synergy effect is particularly high for the manufacture of a single workpiece type in large lot size with a small number of features.

Analogous to the discussion in section 6.2.2, the following considerations will identify the conditions in terms of lot size m, number of features n, changeover time t_{co}, and processing time t_p which maximize the *temporal* synergy effect of equipping a multi-technology platform with a second workspace. The analysis takes place for similar workpiece feeding mode, because due to its simplicity this feeding mode possesses a greater relevance to industry. Furthermore, the relative likelihoods of technology 1 and technology 2 were held constant.

As mentioned above, the temporal synergy effect of a second workspace is influenced by the ability to change over one workspace while the respective other workspace is still processing workpieces. Obviously, one may take particular advantage of this unique ability of double workspace multi-technology platforms in a domain in which one or two workspaces are changed over during large proportions of the reference period T.

The proportion of changeover time during the reference period T depends on the lot size m, the number of features n, the changeover time t_{co}, and the processing time t_p. In a domain of large lot size, large number of features, high processing time, but small changeover time relatively few changeover operations are performed in comparison to a domain of small lot size, small number of features, small processing time, but high changeover time. Hence, the effect of process-simultaneous changeover is particularly high for small lot sizes, small number of features, small processing time but high changeover time.

In figure 7.8 the enhancement of productivity due to process-simultaneous workspace changeover was quantified for exemplary values. A larger potential productivity increase by adaption of the workpiece domain to the outline of the temporal synergy effect of process-simultaneous workspace changeover prevailed for configuration 1.



Impact	m_μ [-]	n_μ [-]	t_{co} [min]	$t_{p,\mu}$ [min]
Great	5	5	6,25	0,50
Small	25	10	1,25	1,25

Simulation period
$T = 12500$ min
Simulation repetitions
$SR = 10$
Workpiece spectrum
$N = 5$
Lot size
$m_\sigma = 1$
Workiece complexity
$n_\sigma = 2$
Processing time
$t_{p,\sigma} = 0{,}25$ min
Rel. likelihood T1
$RL_{T1} = 70\%$
Rel. likelihood T2
$RL_{T2} = 30\%$
Similar workp. feed.

Figure 7.8: Impact of process-simultaneous changeover on productivity
Einfluss des prozesssimultanen Rüstens auf die Produktivität

7.2.2 Relative profitability

This section discusses the relative profitability of double workspace multi-technology platforms of either configuration in comparison to single workspace multi-technology platforms and segregated manufacturing systems. The discussion is based on the productivity considerations made in the recent section with regard to similar workpiece feeding mode. The focus is put on similar workpiece feeding mode because this mode is considered to be most relevant for industrial applications.

In section 6.2.4 it was concluded that the hurdle for relative profitability of integrated manufacturing systems is lower in a domain of low output quantities ($x < x_{crit,IMS}$) than for high output quantities ($x \rightarrow \infty$). Firstly, the relative profitability of double workspace multi-technology platforms will be considered in a domain of low output quantities ($x < x_{crit,2WS}$). Secondly, relative profitability for high output quantities will be discussed ($x \rightarrow \infty$).

Relative profitability for low output quantities ($x < x_{crit,2WS}$)

In section 7.1.2 it was argued that the system cost of double workspace multi-technology platforms is higher than the system cost of single workspace multi-technology platforms. If the operator cost and the indirect consumption cost are assumed to be equal for both alternatives this signifies that the variable indirect cost of a double workspace multi-technology platform $c_{v,i,2WS}$ exceeds the variable indirect cost of a single workspace multi-technology platform $c_{v,i,1WS}$:

$$c_{v,i,2WS} > c_{v,i,1WS} \tag{7.7}$$

Hence, single workspace multi-technology platforms are more profitable for output quantities delimited by $x_{crit,1WS}$. Beyond the critical output of a single workspace multi-technology platform $x_{crit,1WS}$ and below the critical output of a double workspace multi-technology platform two single workspace multi-technology platforms are required. Within this output domain double workspace multi-technology platforms are more profitable if their variable indirect cost $c_{v,i,2ws}$ is smaller than the variable indirect cost of two single workspace multi-technology platforms $2 \cdot c_{v,i,1ws}$:

$$\pi_{2WS} > \pi_{1WS} \Leftrightarrow c_{v,i,2WS} < 2 \cdot c_{v,i,1WS}, \qquad x_{crit,1WS} < x \leq x_{crit,2WS} \tag{7.8}$$

Figure 7.9 depicts the region of relative profitability the double workspace multi-technology platform between $x_{crit,1WS}$ and $x_{crit,2WS}$.

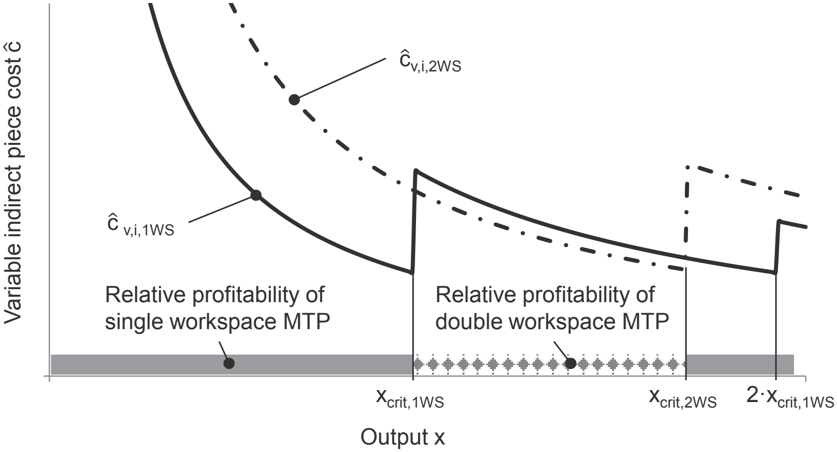


Figure 7.9: Relative profitability of single and double workspace MTP

Relative Profitabilität von Einzel- und Doppelarbeitsraum MTP

Subsequently, the conditions for higher relative profitability of each configuration will be identified for output quantities smaller than $x_{crit,2WS}$ under the assumptions made in section 7.1.2. This comparison in terms of variable indirect piece cost $\hat{c}_{v,i}$ stipulates the consideration of system cost C_{sys} as well as critical output x_{crit} of either configuration. Taking into account expressions (7.2) and (7.3) the system cost of configuration 1 $C_{sys,config\_1}$ is smaller than the system cost of configuration 2 $C_{sys,config\_2}$ if the additional cost for a traveling unit $\Delta C_{sys,TU}$ undercuts the additional cost for an additional technology resource $\Delta C_{sys,TR}$.

$$C_{sys,Config\_1} < C_{sys,Config\_2} \Leftrightarrow \Delta C_{sys,TU} < \Delta C_{sys,TR} \tag{7.9}$$

whereas

$$C_{sys,Config\_1} > C_{sys,Config\_2} \Leftrightarrow \Delta C_{sys,TU} > \Delta C_{sys,TR} \tag{7.10}$$

The critical output x_{crit} of either double workspace configuration was studied in the recent section 7.2.1. In similar workpiece feeding mode, the relative productivity of configuration 1 and 2 assumed almost equal values for relative likelihoods of technology 1 RL_{T1} between 0 % and 50 %, see figure 7.6. Hence, within this value range the relative profitability of configuration 1 and 2 depends solely on the relative system cost C_{sys}, see case i and case ii in figure 7.10.

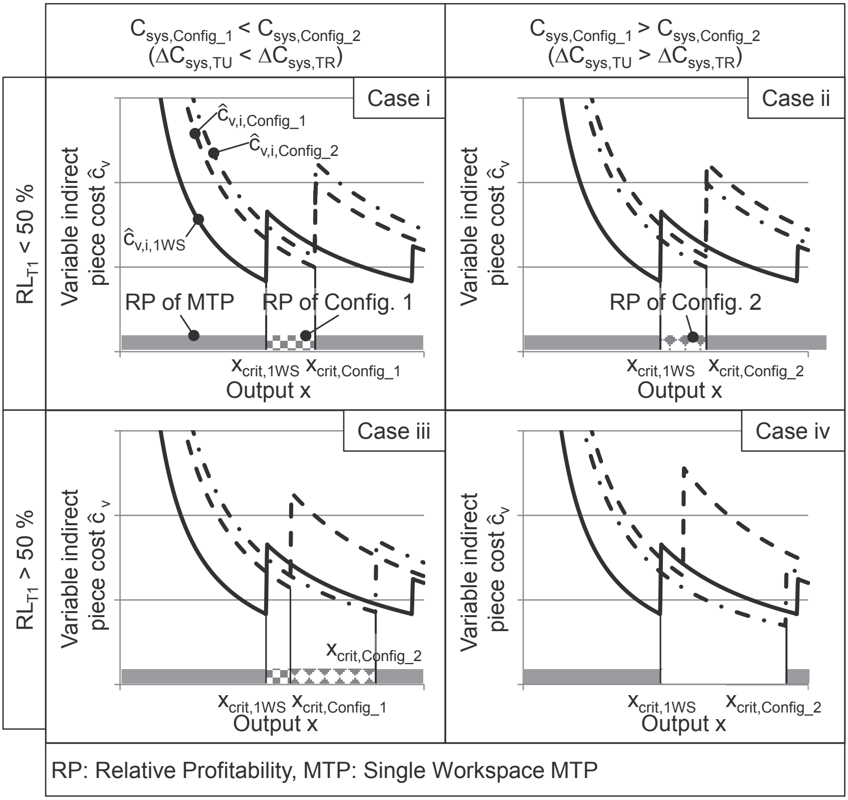


Figure 7.10: Case distinction for relative profitability of double workspace MTP
Fallunterscheidung für relative Profitabilität von MTP

Beyond a relative likelihood of technology 1 RL_{T1} of 50 % an increasing gap exists between the critical output of configuration 1 and 2. In case iv smaller system cost assure relative profitability of configuration 2, see figure 7.10. However, in case iii opposite tendencies with regard to system cost C_{sys} and critical output x_{crit} prevail between configuration 1 and configuration 2. While the system cost of configuration 2 $C_{sys,Config\_2}$ exceeds the system cost of configuration 1 $C_{sys,Config\_1}$, the critical output

$x_{crit,Config\_2}$ is higher than the critical output $x_{crit,Config\_1}$. Hence, beyond the critical output of a single workspace multi-technology platform $x_{crit,1WS}$ and below the critical output $x_{crit,Config\_1}$ configuration 1 is most profitable, see case iii in figure 7.10. Configuration 2 yields more benefits beyond $x_{crit,Config\_1}$ and below $x_{crit,Config\_2}$.

Double workspace multi-technology platforms are more profitable than segregated manufacturing systems for low output quantities ($x < x_{crit,2WS}$) if the variable indirect cost of double workspace multi-technology platforms $c_{v,i,2WS}$ are smaller than the variable indirect cost of a serial line of unparalleled single-technology machine tools:

$$\pi_{2WS} > \pi_{SMS} \Leftrightarrow c_{v,i,2WS} < \chi_{v,i,2WS}(x < x_{crit,2WS}) = \sum_{l=1}^{L_{serial,SMS}} c_{v,i,SMS,l} \tag{7.11}$$

The progression of the productivity limit of the double workspace multi-technology platform and the segregated manufacturing system over the relative likelihood of technology 1 were similar to each other in similar workpiece feeding mode, see figure 7.6. No region exists in which the productivity of the double workspace multi-technology platform of configuration 1 is significantly higher than the productivity of the segregated manufacturing system. In consequence, no large cost difference prevails between the saw-tooth shapes of the variable indirect piece cost $\hat{c}_{v,i,Config\_2}$ and $\hat{c}_{v,i,SMS}$, see left diagram in figure 7.11.

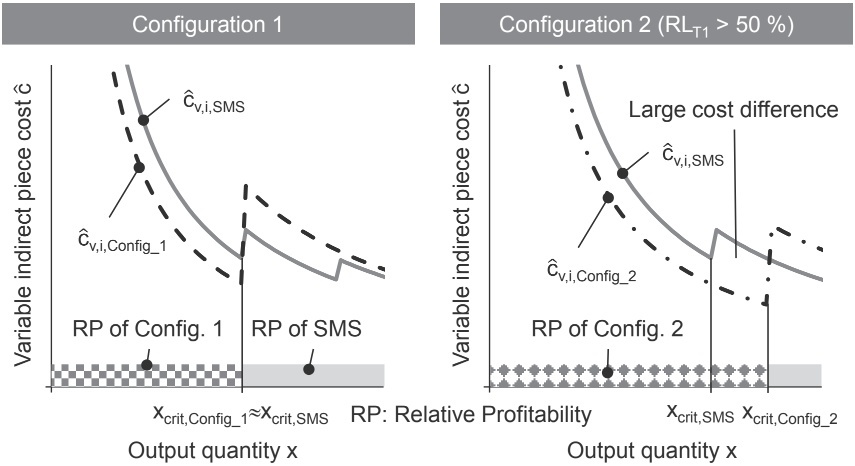


Figure 7.11: Relative profitability of double workspace MTP and SMS

Relative Profitabilität von Doppelarbeitsraum MTP und SMS

The productivity limit of a double workspace multi-technology platform of configuration 2 $x_{crit,Config\_2}$ is higher than the productivity limit of a segregated manufacturing system $x_{crit,SMS}$ if the relative likelihood of technology 1 exceeds 50 %, see figure 7.6. Hence, a double workspace multi-technology platform of configuration 2 may compete with a segregated manufacturing system that comprises paralleled single-technology machine tools. Thus, a double workspace multi-technology platform of configuration 2 is particularly profitable in comparison to a segregated manufacturing system for output quantities beyond $x_{crit,SMS}$ because a large cost difference prevails between variable indirect piece cost in this region, see right diagram in figure 7.11.

Relative profitability for high output quantities (x → ∞)

For high output quantities multi-technology platforms need to be paralleled such that the integrated manufacturing system provides the required productivity. Analogous to expression (6.70), double workspace multi-technology platforms are more profitable than single workspace multi-technology platforms if their variable indirect cost $c_{v,i,2WS}$ undercuts the variable indirect cost threshold $\chi_{v,i,2WS}$ for high output quantities:

$$c_{v,i,2WS} < \chi_{v,i,2WS}(x \rightarrow \infty) = \overbrace{\frac{x_{crit,2WS}}{x_{crit,1WS}}}^{R_{max}} \cdot c_{v,i,1WS} \tag{7.12}$$

Hence, the ratio of variable indirect cost must be smaller than the maximum output ratio R_{max} to obtain a higher productivity of double workspace multi-technology platforms for high output quantities:

$$\frac{c_{v,i,2WS}}{c_{v,i,1WS}} < R_{max} \tag{7.13}$$

As can be seen in figure 7.6 the maximum output ratio R_{max} depends on the relative likelihood of technology 1 RL_{T1} during the machining of workpieces. The preferred operation range of double workspace multi-technology platform of configuration 1 lies between RL_{T1} = 40 % and RL_{T1} = 60 %. In this region, R_{max} assumes a value of roughly 1,5. Therefore, the variable indirect cost ratio $c_{v,i,2WS}/c_{v,i,1WS}$ should be smaller than 1,5 for double workspace multi-technology platforms of configuration 1.The preferred operation range of double workspace multi-technology platforms of configuration 2 lies beyond RL_{T1} = 70 %. In this region, double workspace multi-technology platforms of configuration 2 are approximately twice as productive as single workspace multi-technology platforms, see figure 7.6. Thus, the variable indirect cost ratio $c_{v,i,2WS}/c_{v,i,1WS}$ should be smaller than 2 for double workspace multi-technology platforms of configuration 2.

7.2.3 Relative throughput time

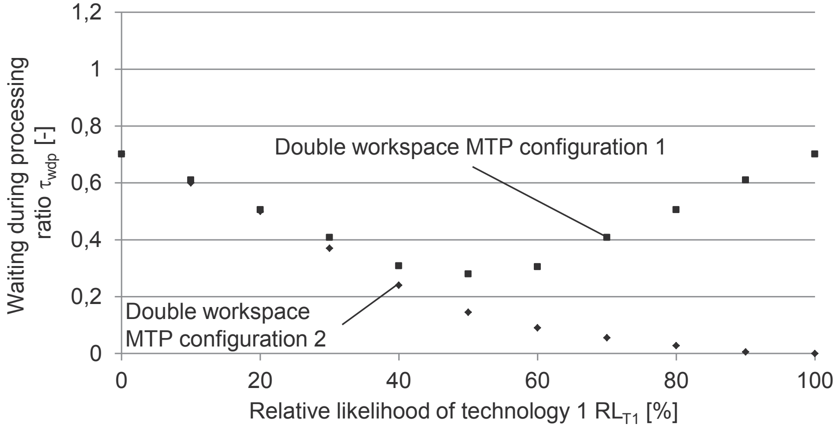
This section studies relative throughput time of double and single workspace multi-technology platforms in similar and complementary workpiece feeding mode. The results are transferred to compare throughput times of double workspace multi-technology platforms to those of segregated manufacturing systems.

Sections 7.1.1 and 7.2.1 outlined already that within the overloaded state a maximum degree of workspace interactions occurs, compare figure 7.3. As a consequence of workspace interaction workpieces have to wait during processing until the currently required technology resource is available. Depending on workpiece complexity and the exact manufacturing sequence multiple waiting periods may increase waiting times during processing significantly.

In general, throughput time analysis within the overloaded state is illegitimate since queues and thus waiting times before processing t_{wbp} grow over the simulation period T. However, waiting times during processing t_{wdp} remain unaffected by the length of queues in front of double workspace multi-technology platforms. In fact, within the overloaded state these waiting times assume maximum but constant values. Hence, through the study of waiting time during processing t_{wdp} in the overloaded state the upper bounds of additional throughput time due to workspace interaction in comparison to a single workspace multi-technology platform may be estimated. To facilitate the comparison to thoughput times of single workspace multi-technology platforms depicted in section 6.2.5 the waiting times during processing t_{wdp} are related to operation times t_{op}. This ratio will be called the waiting time during processing ratio τ_{wdp}.

$$\tau_{wdp} = \frac{t_{wdp}}{t_{op}} \tag{7.14}$$

Figure 7.12 depicts the progression of ratio τ_{wdp} over the relative likelihood of technology 1 RL_{T1} for double workspace multi-technology platforms of configuration 1 and 2 in similar workpiece feeding mode.



Simulation period
T = 2500 min

Simulation repetitions
SR = 10

Workpiece spectrum
N = 5

Lot size
m_μ = 5
m_σ = 1

Workiece complexity
n_μ = 10
n_σ = 2

Processing time
$t_{p,\mu}$ = 0,75 min
$t_{p,\sigma}$ = 0,25 min

Changeover time
t_{co} = 7,50 min

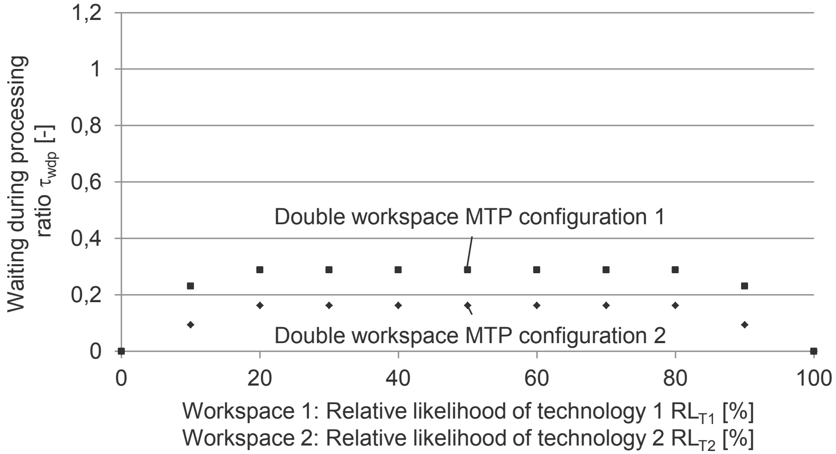
Relative likelihood technology 2
RL_{T2} = $1-RL_{T1}$

Figure 7.12: Waiting during processing ratio τ_{wdp} in similar workpiece feeding mode

Verhältnis τ_{wdp} bei Zufuhr von gleichen Werkstücken

The progressions of the ratio τ_{wdp} of either configuration reflect those of relative productivity shown in figure 7.6. Within the region of optimal productivity the ratio τ_{wdp} assumes minimal values for either configuration. For configuration 1 the preferred operation range in terms of relative likelihood of technology 1 lies between RL_{T1} = 40 % and RL_{T1} = 60 %, compare figure 7.6. For the set of exemplary boundary conditions the ratio τ_{wdp} assumed a mean value of 0,3, see figure 7.12. The relative productivity of configuration 2 in comparison to a single workspace multi-technology platforms is highest beyond a relative likelihood of technology 1 RL_{T1} = 70 %. Within this value range almost no waiting time during processing occurred under the exemplary boundary conditions.

Figure 7.13 illustrates ratio τ_{wdp} of either platform over the relative likelihood of technology 1 RL_{T1} based on discrete-event simulation carried out in complementary workpiece feeding mode.



Simulation period
T = 2500 min
Simulation repetitions
SR = 10
Workpiece spectrum
N = 5
Lot size
m_μ = 5
m_σ = 1

Workiece complexity
n_μ = 10
n_σ = 2

Processing time
$t_{p,\mu}$ = 0,75 min
$t_{p,\sigma}$ = 0,25 min

Changeover time
t_{co} = 7,50 min

Workspace 1
RL_{T2} = 1-RL_{T1}

Workspace 2
RL_{T1} = 1-RL_{T2}

Figure 7.13: Wait. during processing ratio τ_{wdp} in complementary workpiece feeding mode

Verhältnis τ_{wdp} bei Zufuhr von komplementären Werkstücken

Again, both progressions reflect those of relative productivity depicted in figure 7.7. It may be concluded that complementary workpiece feeding mode possesses a positive effect on waiting times during processing t_{wdp} as the ratio τ_{wdp} assumed a value of just below 0,3 for all relative likelihoods of technology 1 RL_{T1} between 10 % and 90 %, see figure 7.13. Complementary workpiece feeding mode possesses a rather contrary effect on the ratio τ_{wdp} for configuration 2. Beyond relative likelihoods of technology 1 RL_{T1} of 50 % only a slight decrease of ratio τ_{wdp} in comparison to similar workpiece feeding mode was observable, compare figure 7.12. Therefore, the installation of an additional technology resource 1 does not lead to a significant reduction of throughput times in complementary workpiece feeding mode.

The simulation results depicted in figure 7.7 and figure 7.13 lead to the conclusion that complementary workpiece feeding mode should be considered for configuration 1 only. Still, it is expected that difficulties accompany the practical implementation of complementary workpiece feeding mode in industry. Most importantly, complementary workpiece feeding mode stipulates the adaption of the entire value stream of workpieces to locally optimize the performance of a double workspace multi-technology platform.

Finally, the implications of the recent considerations will be transferred to relative throughput times of double workspace multi-technology platforms and segregated manufacturing systems. The throughput time comparison between single workspace multi-technology platforms and segregated manufacturing systems in section 6.2.5 lead to the conclusion that a transportation time ratio $\Delta t_{r,SMS}$ of four ensured smaller throughput times through technology integration, compare figure 6.17.

If a double workspace multi-technology platform of configuration 1 is operated under optimal conditions with regard to the relative likelihood of technology 1 ($40\ \% < RL_{T1} < 60\ \%$) the occupancy duration of workspaces is increased by 30 % per workpiece in comparison to a single workspace multi-technology platform due to waiting during processing, compare figure 7.8. Thus, the operation time ratio τ_{op} between a double workspace multi-technology platform and a segregated manufacturing system assumes a higher value than the respective ratio of a single workspace multi-technology platform. As a consequence, throughput times of double workspace multi-technology platforms of configuration 1 are only shorter than throughput times of segregated manufacturing systems if the transportation time ratio $\tau_{tr,SMS}$ assumes a value greater than 4, compare figure 6.17. In other words, it is more likely that throughput times of configuration 1 are higher than those of segregated manufacturing systems in comparison to single workspace multi-technology platforms.

Contrarily, throughput times of double workspace multi-technology platforms of configuration 2 hardly increase in comparison to single workspace multi-technology platforms within their optimal operation range ($RL_{T1} > 70\ \%$). Thus, a transportation time ratio $t_{tr,SMS}$ of 4 ensures smaller throughput times in comparison to segregated manufacturing systems, compare figure 6.17

7.3 Implications for the design of double workspace multi-technology platforms

Three major design implications based on the recent relative economic efficiency considerations of double workspace multi-technology platforms will be reflected within this section. The first implication relates to the conditions under which equipping a multi-technology platform with a second workspace should be considered at all. Second, the criteria for selecting the adequate configuration will be discussed. The final considerations elaborate on the necessity to install additional safety measures to allow for process-simultaneous workspace changeover.

The temporal synergy effect may be significantly enhanced by equipping a multi-technology platform with a second workspace. However, the second workspace, the additional traveling units, and technology resources etc. elevate the system cost significantly. Due to the opposing effects on productivity and system cost no universally valid judgement on the advantageousness of double workspace multi-technology platforms may be drawn. In fact, relative economic efficiency of double workspace multi-technology platforms must be determined for each combination of manufacturing technologies individually. However, a clear tendency exists with regard to type of manufacturing technologies to be integrated in double workspace multi-technology platforms which will be discussed in the following.

Section 6.4.2 and the introduction to this chapter outlined that the direct functional synergy effect contributes greatly to relative economic efficiency of single workspace multi-technology platforms. Due to the remote location of technology resources within double workspace multi-technology platforms one may not take advantage of direct functional synergy between the manufacturing technologies to create a monetary synergy effect. Thus, a large system cost difference may be expected between single and double workspace multi-technology platforms if functionally similar manufacturing technologies are integrated. As a consequence relative economic efficiency of double workspace multi-technology platforms may be regarded as rather low for functionally similar manufacturing technologies.

Contrarily, if manufacturing technology integration of functionally dissimilar manufacturing technologies is considered the expected system cost difference between single and double workspace multi-technology platforms is not quite as pronounced. This is, because neither the design of single nor the design of double workspace multi-technology platforms may take advantage of direct functional synergy between manufacturing technologies. Hence, relative economic efficiency of double workspace multi-technology platforms prevails in particular for combinations of functionally dissimilar manufacturing technologies.

The considerations of relative economic efficiency in section 7.2 demonstrated the poor competitiveness in terms of productivity, profitability, and throughput time of double workspace multi-technology platforms of configuration 1 in comparison to segregated manufacturing system. A small region of relative profitability of configuration 1 in comparison to configuration 2 exists only if the system cost of an additional technology resource $\Delta C_{sys,TR}$ exceeds the system cost of an additional traveling unit $\Delta C_{sys,TU}$, compare section 7.2.2. If the design of a multi-technology platform does not aim at very particular and static boundary conditions only configuration 2 should be considered. Expression (7.8) and (7.11) determine whether the temporal synergy effects of configuration 2 may overcompensate the additional system cost and assure relative profitability in comparison to single workspace multi-technology platforms and segregated manufacturing systems.

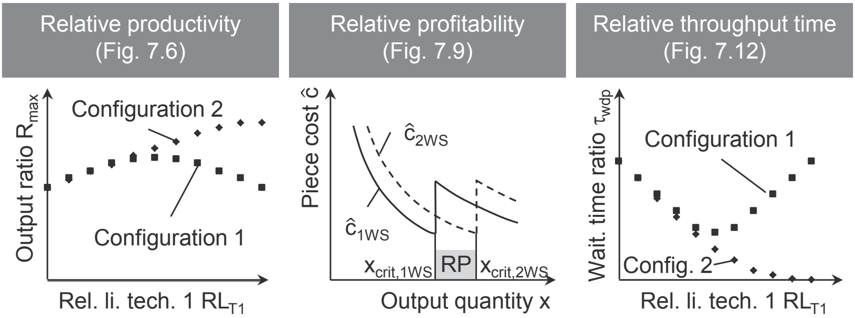
As emphasized in section 7.1.1 process-simultaneous workspace changeover stipulates special safety measures to ensure the physical integrity of the operator. However, the impact of process-simultaneous workspace changeover on the productivity of the preferred configuration 2 remained rather low, compare figure 7.8. Hence, the relatively small additional temporal synergy effect linked to process-simultaneous workspace changeover and the extra cost to install safety measures need to be traded off against each other.

7.4 Interim conclusion

Double workspace multi-technology platforms are based on the idea that at least one technology resource may travel between the workspaces. Thus, the concept of double workspace multi-technology platforms addresses the deficient use of technology resources in single workspace multi-technology platforms.

Figure 7.14 summarises the key findings of section 7.2 “Derivation of efficiency conditions”. Double workspace multi-technology platforms enhance the productivity in comparison to single workspace multi-technology platforms significantly if either the more frequently applied technology resource is installed in either workspace (configuration 2) or if workpieces with complementary properties in terms of technology use are fed to the two workspaces. The latter approach, however, stipulates a comprehensive analysis of workpiece properties as well as a local optimization within the manufacturing chain which must be rejected from a manufacturing systems’ point of view. The preferred operation range of a double workspace multi-technology platform of configuration 2 in terms of productivity relates to workpiece spectra which require a relative likelihood of technology resource beyond 70 %. In this region, a double workspace multi-technology platform may be twice as productive as a single workspace multi-technology platform, compare figure 7.6.

The increase in productivity of double workspace multi-technology platforms in comparison to single workspace multi-technology platforms is based on the installation of an additional workspace as well as additional traveling units, and technology resources. Hence, the productivity increase is linked to additional cost which causes the necessity to ponder productivity over cost. Consequently, no holistic judgement about the benefits of double workspace multi-technology platforms in comparison to single workspace multi-technology platforms may be drawn. In fact, the possibility of equipping a multi-technology platform with a second workspace should be considered within each design process of multi-technology platforms individually.



Key findings

Productivity increase of second workspace depends on relative likelihood of technology 1 and 2

Profitability higher for
- $c_{v,i,2WS} < 2 \cdot c_{v,i,1WS}$
- output quantities beyond $x_{crit,1WS}$ and beneath $x_{crit,2WS}$

Waiting time during processing ratio τ_{wdp} depends on relative likelihood of technology 1 and 2

Figure 7.14: Key findings of chapter 6.2

Hauptergebnisse von Kapitel 6.2

Since technology resources are not available at all times workpieces may have to wait within the workspace until the subsequent manufacturing process initiates. Depending on the configuration of the double workspace multi-technology platform, the workpiece feeding mode, as well as the relative likelihood of technology use throughput times may be increased conspicuously. However, in the preferred operation range of double workspace multi-technology platform of configuration 2 no significantly increase of throughput times was identified in simulations of similar workpiece feeding mode, compare figure 7.12.

Due to the remote installation of technology resources no direct functional synergy between the functional spectra of the manufacturing technologies to be integrated may be exploited in double workspace multi-technology platforms. Therefore, double workspace multi-technology platforms should be considered in particular if no functional similarities prevail between the manufacturing technologies.

8 Economic efficiency of flexible manufacturing

Manufacturing industries are subject to ever-increasing market volatility. The turbulences within the market environment act upon the manufacturing system through so-called receptors like the product type, the output quantities, or the manufacturing cost, compare [NYHU08, p. 23]. In particular, a change in product type influences the functional requirements of the manufacturing system.

Two alternative strategies exist in principle to face varying functional requirements, conventional and flexible manufacturing. The initial functional window of a conventional manufacturing system reflects only the functional requirements of the initial manufacturing system. Intentionally, the functional window is not maximized because future functional requirements are unknown. However, if functional requirements change over the course of time the functional window of the system is adjusted accordingly through the acquisition of additional single-technology machine tools, see figure 8.1. Due to their limited functional window, single-technology machine tools are enablers of conventional manufacturing systems.

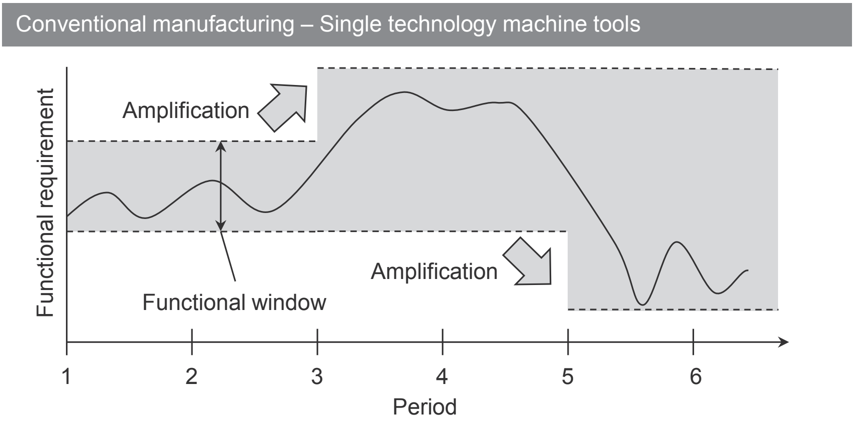

Conventional manufacturing – Single technology machine tools

Figure 8.1: Functional window of conventional manufacturing over the course of time
Funktionales Fenster konventioneller Fertigung im Laufe der Zeit

In contrast to conventional manufacturing the idea of flexible manufacturing is to anticipate future functional requirements a priori and integrate all supposable functions into the initial system. Thus, flexible manufacturing attempts to maximize the functional window of a manufacturing system, see figure 8.2. Multi-technology platforms are enablers of flexible manufacturing because such platforms possess an enhanced functional window in comparison to conventional single-technology machine tools. However, it is of course possible that certain functional requirements are not anticipated during the planning of the flexible manufacturing system. As a consequence, the flexible manufacturing system may not be applied in all future scenarios if it is not amplified like a conventional manufacturing system.

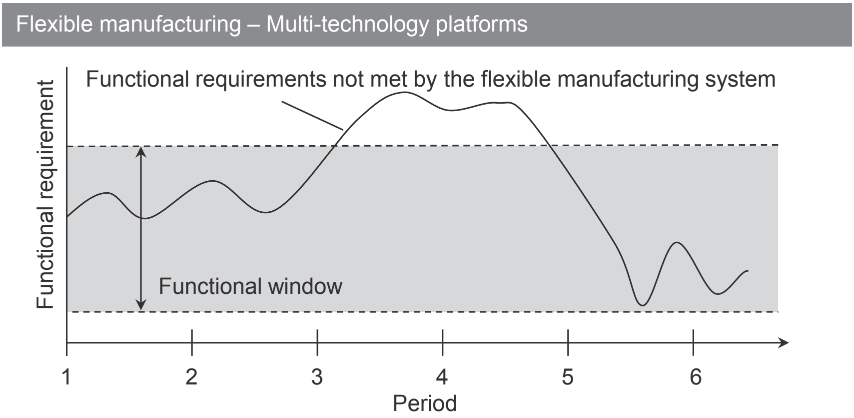


Figure 8.2: Functional window of flexible manufacturing over the course of time

Funktionales Fenster flexible Fertigung im Laufe der Zeit

This chapter discusses the benefits of flexible manufacturing in comparison to conventional manufacturing based on a mathematical model. The model is implemented in section 8.1 and efficiency conditions are derived in section 0. Section 8.3 discusses the implications for the design of multi-technology platforms.

8.1 Model implementation

In the following, it will be assumed that the output quantity x may be produced by a single multi-technology platform and a single conventional machine tool during the reference period T. The fixed cost C_f are neglected. The cost of flexible manufacturing comprises the variable indirect cost of a single-technology machine tool $c_{v,i,SMS}$ and the additional cost ΔC_{flex} the producers is willing to pay to maximize the functional window through installation of a multi-technology platform.

$$C_{flex} = c_{v,i,IMS} = c_{v,i,SMS} + \Delta C_{flex} \qquad (8.1)$$

The variable indirect cost of conventional manufacturing depends on the functional requirements over the course of time. If the functional requirements may be met by a single-technology machine tool no system amplification is required. Hence, the cost of conventional manufacturing is equal to the variable indirect cost of a single-technology machine tool:

$$C_{conv}(\text{No amplification}) = c_{v,i,SMS} \qquad (8.2)$$

If an amplification of the functional window is required the producer needs to pay an additional cost ΔC_{conv} to amplify the manufacturing system:

$$C_{conv}(\text{Amplification.}) = c_{v,i,SMS} + \Delta C_{conv} \qquad (8.3)$$

A change in the functional requirements occurs with a probability p. Thus, the expected cost of conventional manufacturing C_{conv} may be determined by the following expression:

$$C_{conv} = p \cdot (c_{v,i,SMS} + \Delta C_{conv}) + (1 - p) \cdot c_{v,i,SMS} = c_{v,i,SMS} + p \cdot \Delta C_{conv} \tag{8.4}$$

During the reference period T the producer may generate the contribution margin D in case of flexible manufacturing because the manufacturing system is immediately available.

$$D_{flex} = D \tag{8.5}$$

In case of conventional manufacturing, the system needs to be amplified if a change in the functional requirements occurs. During the amplification period t no goods are produced resulting in a reduction of the achievable contribution margin D. The reduction of contribution margin will be described by the reduction factor ρ.

$$\rho = \frac{e^{\frac{t}{\lambda}} - e^{\frac{T_{max}}{\lambda}}}{1 - e^{\frac{T_{max}}{\lambda}}} \tag{8.6}$$

The parameter T_{max} describes the duration of the amplification period t which would reduce the contribution margin D to zero, see figure 8.3. The progressive decline of the reduction factor ρ over the amplification period t is reflected by the parameter λ.

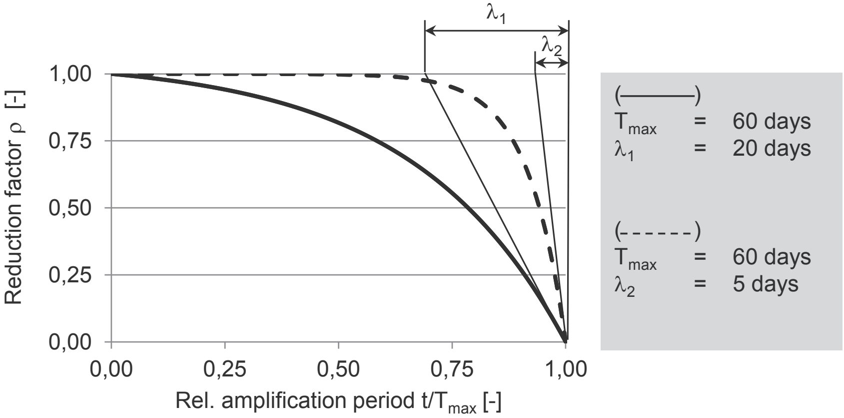


Figure 8.3: Progression of reduction factor over amplification period

Verlauf des Reduzierungsfaktors über der Erweiterungsperiode

The contribution margin is only reduced if the functional requirements change. Otherwise, the contribution margin D may be generated. Hence, the expected value for the contribution margin of conventional manufacturing D_{conv} may be calculated by the following expression:

$$D_{conv} = p \cdot D \cdot \rho + (1 - p) \cdot D = D + p \cdot D \cdot (\rho - 1) \tag{8.7}$$

The profitability π_{flex} and π_{conv} are determined by the difference between contribution margin and cost:

$$\pi_{flex} = D_{flex} - C_{flex} = D - (c_{v,i,SMS} + \Delta C_{flex}) \tag{8.8}$$

$$\pi_{conv} = D_{conv} - C_{conv} = D + p \cdot D \cdot (\rho - 1) - (c_{v,i,SMS} + p \cdot \Delta C_{conv}) \tag{8.9}$$

The profitability model will be applied in the following to identify regions in which flexible manufacturing systems are more profitable than conventional manufacturing systems.

8.2 Derivation of efficiency conditions

Flexible manufacturing is advantageous in comparison to conventional manufacturing if it yields a higher profitability.

$$\pi_{flex} > \pi_{conv} \tag{8.10}$$

In the following, the profitable conditions of flexible manufacturing in terms of probability p and amplification period t will be identified. For this expression (8.8) and expression (8.9) are substituted to inequation (8.10). Flexible manufacturing yields a higher profitability than conventional manufacturing if the probability p for changing functional requirements exceeds the characteristic Π.

$$\pi_{flex} > \pi_{conv} \Leftrightarrow p > \Pi = \frac{\Delta C_{flex}/D}{1 - \rho + \Delta C_{conv}/D} \tag{8.11}$$

Based on expression (8.11), the portfolio depicted in figure 8.4 may be derived. The progression of the curve Π describes all points of equal profitability of flexible and conventional manufacturing. Hence, the plane spanned by probability t and relative reconfiguration period t/T_{max} is subdivided into an area in which flexible manufacturing is more profitable and an area in which conventional manufacturing is more profitable. Flexible manufacturing is efficient in comparison to conventional manufacturing if the probability p for changing functional requirements and the amplification period t are high.

The relative profitability of flexible manufacturing depends on the ratio of flexibility cost to amplification cost $\Delta C_{flex}/\Delta C_{conv}$, see figure 8.4. The higher the additional cost for maximizing the functional spectrum of a multi-technology platform ΔC_{flex} in comparison to the additional cost for conventional manufacturing ΔC_{conv} is the smaller the region of relative profitability of flexible manufacturing.

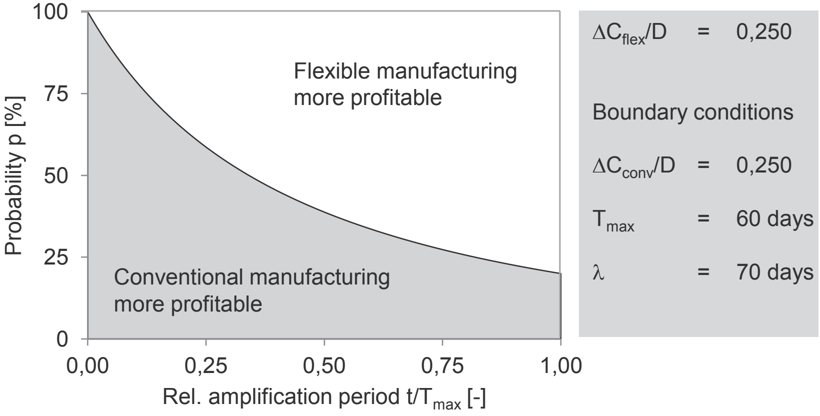


Figure 8.4: Portfolio of flexible and conventional manufacturing
Portfolio flexibler und konventioneller Fertigung

8.3 Implications for the design of multi-technology platforms

The a priori integration of functions into multi-technology platforms follows the idea of flexible manufacturing whereas conventional manufacturing demands a retroactive acquisition of single-technology machine tools to broaden the functional spectrum of the manufacturing system in case a change in the functional requirements occurs. The portfolio in figure 8.4 shows that the integration of additional functions is profitable if the probability p is high that the function is actually applied. This signifies that a multi-technology platform should comprise just those functions which are likely to be used during the reference period T.

Furthermore, the profitable region of flexible manufacturing is enlarged if the cost of adding flexibility ΔC_{flex} to a multi-technology platform in comparison to the additional cost of adding a single-technology machine tool ΔC_{conv} is low. The cost for adding flexibility ΔC_{flex} is low if direct functional synergy between the manufacturing technologies may be exploited by machine tool design, compare section 6.4.2. Hence, the considerations of flexible manufacturing emphasize the necessity to integrate functionally similar manufacturing technologies into multi-technology platforms.

8.4 Conclusion

Flexible manufacturing and conventional manufacturing are two distinct strategies to address the volatility with regards to the functional requirements of the manufacturing system over the course of time. While flexible manufacturing promotes the a priori integration of functions into multi-technology platforms, conventional manufacturing relies on single-technology machine tools that are complemented by further single-technology machine tools if functional requirements change.

The recent considerations have shown that the integration of functions should be taken into account if the probability is high that such functions are actually applied during the reference period T and a large amount of time would be spent to amplify the system. This signifies that the functional spectrum of a multi-technology platform must be adapted to the most likely scenario in terms of functional requirements. Furthermore, direct functional synergy between manufacturing technologies amplifies the profitable region of flexible manufacturing. Hence, functionally similar manufacturing technologies should be integrated in particular.

9 Application

The practical relevance of the results of this thesis will be elucidated by three case studies. Firstly, the machining of a rotary table of a machine tool in low output quantities by an integrated manufacturing system consisting of a single workspace multi-technology platform will be discussed. Secondly, the manufacturing of a drive shaft from the automotive industry in large output quantities by double workspace multi-technology platforms will be presented. Thirdly, the manufacturing of turned parts with and without square features will be elucidated.

9.1 Case study A: Rotary table of a machine tool

Figure 9.1 depicts a rotary table of a machine tool from the workpiece spectrum of a machine tool builder. Workpieces with similar features but distinct geometrical properties are manufactured in lot sizes of m = 10 in low output quantities. The raw material is a casted body which requires milling and drilling in a first step. At the lower side the rotary table possesses two guideways which are to be ground subsequently.

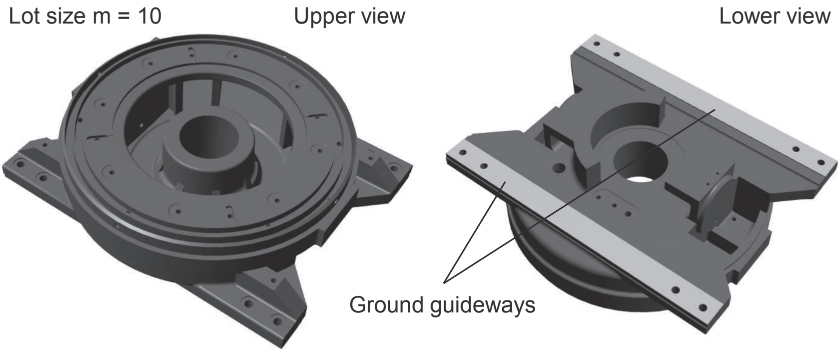
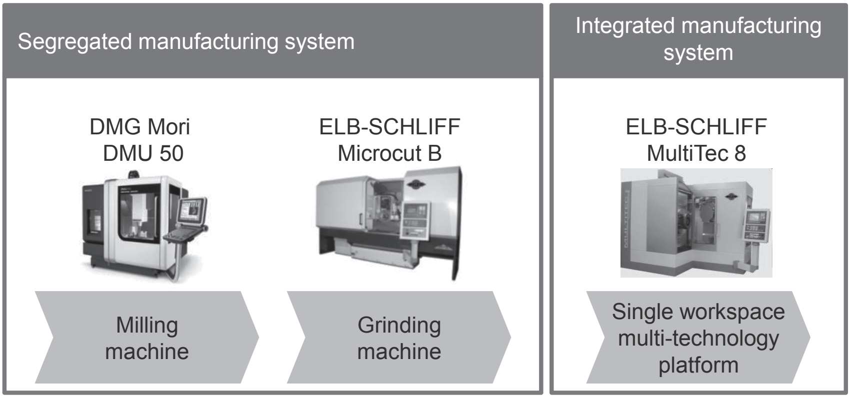


Figure 9.1: Rotary table of machine tool
Rotationstisch einer Werkzeugmaschine

The end machining of the rotary table may either be carried out by a segregated or an integrated manufacturing system. Both manufacturing systems are shown in figure 9.2.

The segregated manufacturing system consists of milling machines of type “DMG Mori DMU 50” and grinding machines of type “ELB-SCHLIFF Microcut B”. The integrated manufacturing system comprises single workspace multi-technology platforms of type “ELB-SCHLIFF MultiTec 8”.

In the following the relative economic efficiency of the integrated and the segregated manufacturing system will be discussed for variable output quantities. The configuration of either manufacturing system is adjusted according to the output quantities to be machined. Hence, the integrated manufacturing system may assume a parallel configuration consisting of multiple single workspace multi-technology platforms whereas the segregated manufacturing system may assume a serial and parallel configuration of multiple milling and grinding machines.



Source of pictures: www.dmgmoriseiki.com, ELB-SCHLIFF

Figure 9.2: Machine tools of segregated and integrated manufacturing system
Werkzeugmaschinen des segregierten und integrierten Fertigungssystems

Table 9-1 illustrates the operation times per lot of the machine tools of the integrated and the segregated manufacturing system. Because of its higher complexity the changeover time of the single workspace multi-technology platform is higher than the changeover time of the single-technology machine tools. The workpiece change time may be reduced through manufacturing technology integration since the milling and grinding operations at the lower side of the rotary table are machined in a single clamping. The processing time per workpiece of the multi-technology platform is higher than the processing time per workpiece of the single-technology machine tools because more processes are carried out on the multi-technology platform.

Table 9-1: Operation times per lot of segregated and integrated manufacturing system

	Milling machine	Grinding machine	Single workspace MTP
Changeover time per lot $t_{co,j}$ [min]	15	15	20
Workpiece change time per workpiece $t_{wc,j}$ [min]	1	2	1
Processing time per workpiece $t_{p,j}$ [min]	15	8	22
Operation time per lot $t_{op,j}$ [min]	175	115	250

The relative profitability of manufacturing technology integration will be discussed during a reference period of four weeks and for a variable number of orders, see table 9-2. During the reference period of four weeks (T = 160 h) the machine tools are used to a maximum mean utilization of $U_{m,max}$ = 80 %. This signifies that the maximum operation time of the machine tools during the reference period T_{op} is equal to 128 hours.

Table 9-2: Duration of reference period and maximum operation time

Weeks	Days per week	Shifts per day	Hours per shift	Reference period T [h]	Maximum mean utilization $U_{m,max}$	Maximum operation time T_{op} [h]
4	5	1	8	160	80 %	128

Table 9-3 shows the cost of the integrated and the segregated manufacturing system during the reference period T and the variable indirect cost $c_{v,i}$ consists of the machine cost c_{MT} and the operator cost C_{oper}. It is assumed that each machine tool is run by a single operator. The critical output o_{crit} of each machine tool in terms of lots manufacturable during the reference period T is determined by the following expression:

$$o_{crit} = \text{floor}\left(\frac{T_{op}}{t_{op}}\right) \tag{9.1}$$

Although the total operation time within the integrated manufacturing system is shorter than the total operation time within the segregated manufacturing system, the integrated manufacturing system possesses a smaller critical output. This is because the total workload may be distributed on two machines within the segregated manufacturing system whereas the total workload is carried by a single multi-technology platform.

Table 9-3: Cost during reference period T

	Milling machine	Grinding machine	Single workspace MTP
Machine cost $c_{MT,j}$ [€]	1.076,92	1.846,15	5.384,62
Operator cost $c_{oper,j}$ [€]	4.800,00	4.800,00	4.800,00
Variable indirect cost $c_{v,i,j}$ [€]	5.876,92	6.646,15	10.184,62
Critical output $o_{crit,j}$ [qty.]	43	66	30
$c_{v,i,j}/x_{crit,j}$ [€/qty.]	13,67	10,07	33,95

According to expression (6.68) the integrated manufacturing system is more profitable in a domain delimited by the critical output o_{crit} = 30 if its variable indirect cost $c_{v,i,IMS}$ is smaller than the variable indirect cost of the segregated manufacturing system $c_{v,i,SMS}$. This is the case for the exemplary values depicted in table 9-3:

$$c_{v,i,IMS} = 10.184{,}62\ \text{€} < c_{v,i,SMS}(x<x_{crit,IMS}) = 5.876{,}92\ \text{€} + 6.646{,}15\ \text{€} = 12.363{,}07\ \text{€} \qquad (9.2)$$

For high output quantities the cost to productivity ratio according to expression (6.69) needs to be considered. The relative profitability condition for high output quantities is not fulfilled for the exemplary values. Hence, the segregated manufacturing system is more profitable than the integrated manufacturing system for high output quantities.

$$\hat{c}_{v,i,IMS}(\infty) = \frac{c_{v,i,IMS}}{x_{crit,IMS}} = 33{,}95\ \text{€} \nless \hat{c}_{v,i,SMS}(\infty) = 13{,}67\ \text{€} + 10{,}07\ \text{€} = 23{,}74\ \text{€} \qquad (9.3)$$

Figure 9.3 illustrates the progression of the variable indirect piece cost $\hat{c}_{v,i,IMS}$ and the configuration of the manufacturing system over the number of orders o. As can be seen the integrated manufacturing system yields smaller variable indirect piece cost in a output domain delimited by $o_{crit,IMS}$. However, due to a smaller cost to productivity ratio the segregated manufacturing system is more profitable beyond o_{crit}.

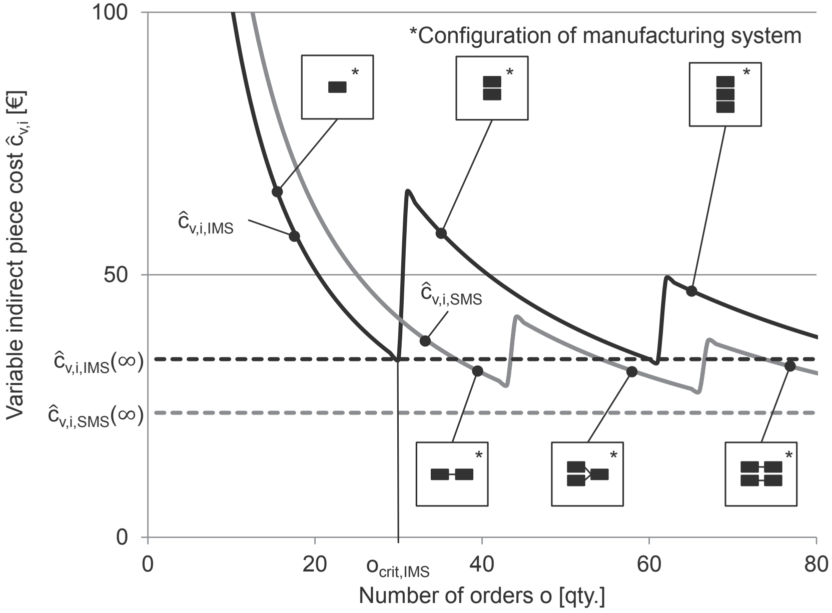


Figure 9.3: Progression of variable indirect piece cost over number of orders
Verlauf der variablen indirekten Stückkosten über der Anzahl der Aufträge

Figure 9.4 depicts the progression of throughput time over the number of orders o under the assumption of exponentially distributed interarrival times of orders and a transportation time of t_{tr} = 10 min between the milling machine and the grinding machine of the segregated manufacturing system.

For both manufacturing systems the throughput time exceeds the operation time due to waiting of orders in front of machines that are occupied. For low output quantities delimited by o_{crit} the average utilization of the integrated manufacturing system is higher than the average utilization of the segregated manufacturing system. Hence, the increase of throughput times over the number of orders is more pronounced in case of manufacturing technology integration. In fact, the higher waiting times within the integrated manufacturing system overcompensate the smaller operation times for o ≥ 13. In consequence, the throughput time of the integrated manufacturing system exceeds the throughput time of the segregated manufacturing system.

Beyond the critical output of the integrated manufacturing system $o_{crit,IMS}$ multi-technology platforms are paralleled. The parallelization of multi-technology platforms decreases the average utilization and thus lowers the throughput times in comparison to the segregated manufacturing system.

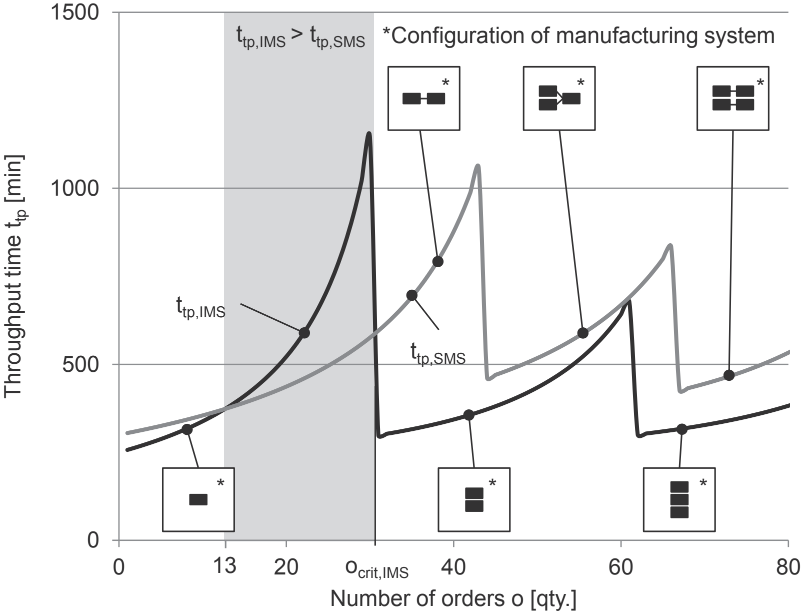


Figure 9.4: Progression of throughput time over number of orders

Verlauf der Durchlaufzeit über der Anzahl der Aufträge

Case study A illustrates that manufacturing technology integration with single workspace multi-technology platforms leads to smaller piece cost in a domain of low output quantities in particular. Thus, manufacturing technology integration should be considered for output quantities smaller than the productivity limit of a single multi-technology platform $o_{crit,IMS}$. However, in this domain throughput times of a single multi-technology platform are likely to be higher than throughput times of a segregated manufacturing system due to higher resource utilization.

9.2 Case study B: Drive shaft

Figure 9.5 depicts an exemplary drive shaft out of the workpiece spectrum of a supplier of the automotive industry. All drive shafts of the workpiece spectrum comprise similar workpiece features but differ with regard to the geometrical dimensions. The workpiece features are a carrier at one end of the drive shaft, a centre hole equipped with a thread, a knurl and two bearing seats. In the following, the soft machining of such drive shafts will be discussed.

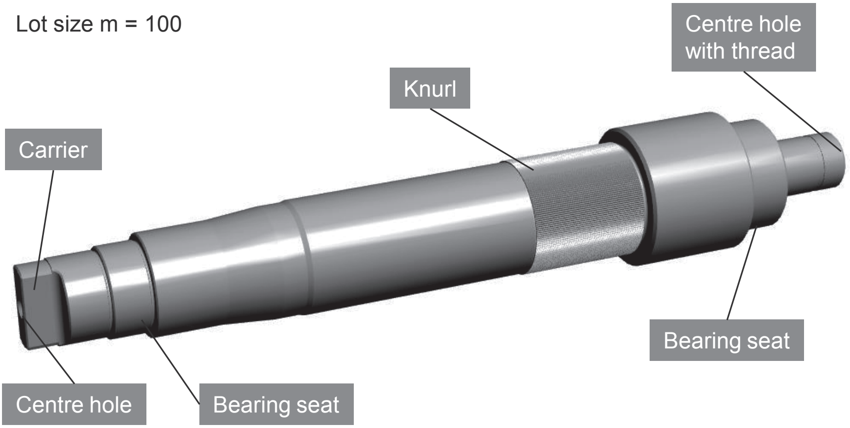
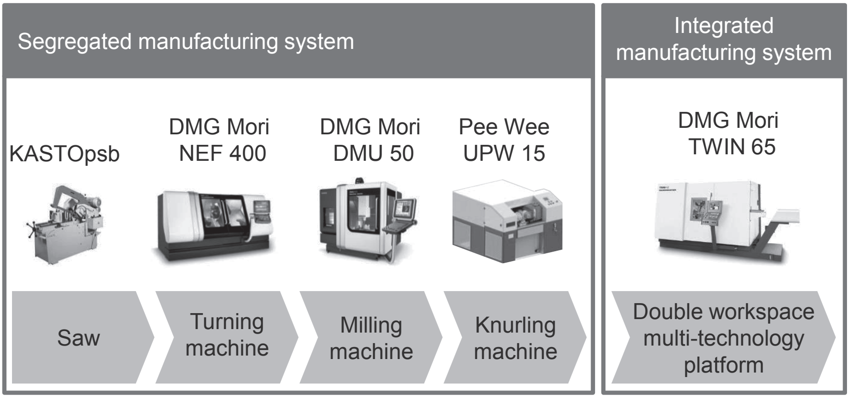


Figure 9.5: Drive shaft
Antriebswelle

Two alternative ways exist to carry out the soft machining of the drive shafts, either through a segregated or through an integrated manufacturing system. Figure 9.6 shows the elements of both alternative manufacturing systems. The segregated manufacturing system consists of a saw, a turning machine, a milling machine, and a knurling machine which are connected in series. The number of machine tools at each transformation step is adjusted according to the number of orders to be manufactured. Hence, the segregated manufacturing system may assume a serial and parallel configuration, compare figure 6.3.

The integrated manufacturing system consists of double workspace multi-technology platforms in parallel configuration. The DMG Mori TWIN 65 is a two spindle turning centre which may perform all machining operations required to carry out the soft machining of the drive shafts. The turning centre comprises two workpiece spindles which allow the simultaneous manufacture of two workpieces in parallel.



Source of pictures: www.kasto.de, www.dmgmoriseiki.com, www.pee-wee.de

Figure 9.6: Machine tools of segregated and integrated manufacturing system
Werkzeugmaschinen des segregierten und integrierten Fertigungssystems

Figure 9.7 and figure 9.9 depict the process chains of the segregated and the integrated manufacturing system. The respective operation times per lot consisting of m = 100 workpieces for both manufacturing systems may be found in table 9-4.

Figure 9.8 shows that both workpiece spindles are involved in the processing of the drive shafts. The manufacture of features at the left side of the drive shaft takes place while the workpiece is still connected to the rod. After cutting-off, the drive shaft is passed to the secondary workpiece spindle and the manufacture of features at the right side is carried out.

Table 9-4: Operation times per lot of segregated and integrated manufacturing system

	Saw	Turning machine	Milling machine	Knurling machine	Double workspace MTP
Changeover time per lot $t_{co,j}$ [min]	5,0	20,0	10,0	10,0	25,0
Workpiece change time per workpiece $t_{wc,j}$ [min]	0,2	0,3	0,3	0,1	0,4
Processing time per workpiece $t_{p.j}$ [min]	0,5	1,0	0,3	0,3	1,3 (main workpiece spindle)
Operation time per lot $t_{op,j}$ [min]	75,0	150,0	70,0	50,0	195,0

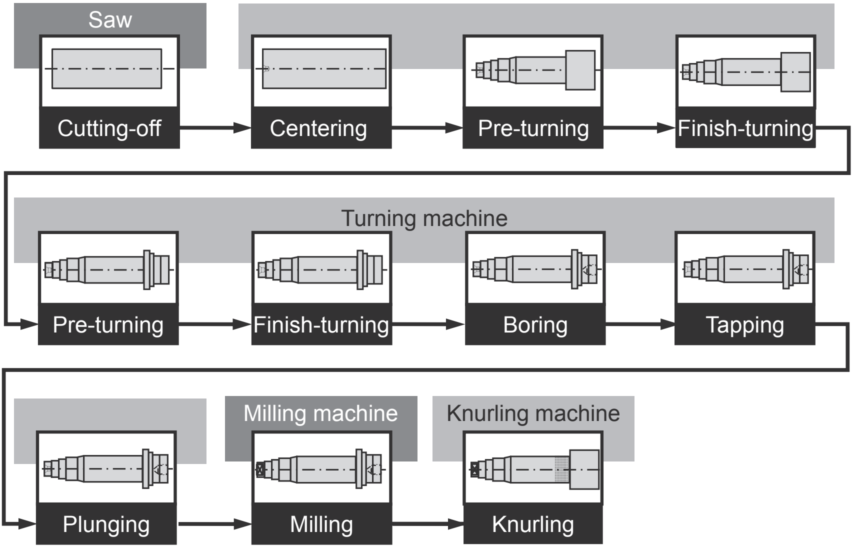


Figure 9.7: Process chain of segregated manufacturing system

Prozesskette des segregierten Fertigungssystems

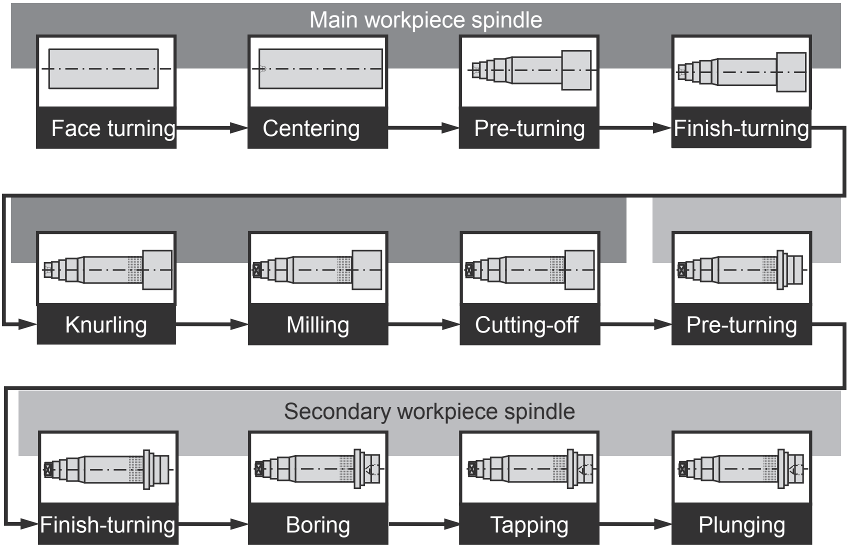


Figure 9.8: Process chain of integrated manufacturing system

Prozesskette des integrierten Fertigungssystems

Similar to case A the relative profitability of manufacturing technology integration will be considered during a reference period of four weeks. Table 9-5 depicts the cost during the reference period T. The critical output $o_{crit,j}$ was determined according to expression (9.1).

Table 9-5: Cost during reference period T

	Saw	Turning machine	Milling machine	Knurling machine	Double workspace MTP
Machine cost $c_{MT,j}$ [€]	153,85	1.076,92	1.076,92	615,39	1.846,15
Operator cost $c_{oper,j}$ [€]	4.800,00	4.800,00	4.800,00	4.800,00	4.800,00
Variable indirect cost $c_{v,i,j}$ [€]	4.953,85	5.876,92	5.876,92	5.415,38	6.646,15
Critical output $o_{crit,j}$	102	51	109	153	39
$c_{v,i,j}/x_{crit,j}$	0,49	1,15	0,54	0,35	1,70

For low output quantities the integrated manufacturing system is more profitable if its variable indirect cost $c_{v,i,IMS}$ is smaller than the cumulated variable indirect cost of the segregated manufacturing system, see expression (6.68). As can be seen, this is the case for the exemplary values depicted in table 9-5.

$$c_{v,i,IMS} = 6.645{,}15 \text{ €} < c_{v,i,SMS}(x < x_{crit,IMS}) = \sum c_{v,i,j} = 22.129{,}07 \text{ €} \tag{9.4}$$

For high output quantities the cost to productivity ratio needs to be taken into account, compare expression (6.69). As opposed to case A the cost to productivity ratio of the integrated manufacturing system are also smaller than the cost to productivity ratio of the segregated manufacturing system. Hence, the integrated manufacturing possesses a higher profitability than the segregated manufacturing system for any output quantity.

$$\hat{c}_{v,i,IMS}(\infty) = \frac{c_{v,i,IMS}}{x_{crit,IMS}} = 1{,}70 \text{ €} < \hat{c}_{v,i,SMS}(\infty) = \sum \frac{c_{v,i,j}}{x_{crit,j}} = 2{,}53 \text{ €} \tag{9.5}$$

Figure 9.9 illustrates the progression of variable indirect piece cost $\hat{c}_{v,i,IMS}$ and the configuration of the integrated and the segregated manufacturing system over the number of orders o to be produced. The figure shows that the integrated manufacturing system possesses smaller variable indirect piece cost than the segregated manufacturing system for any output quantity.

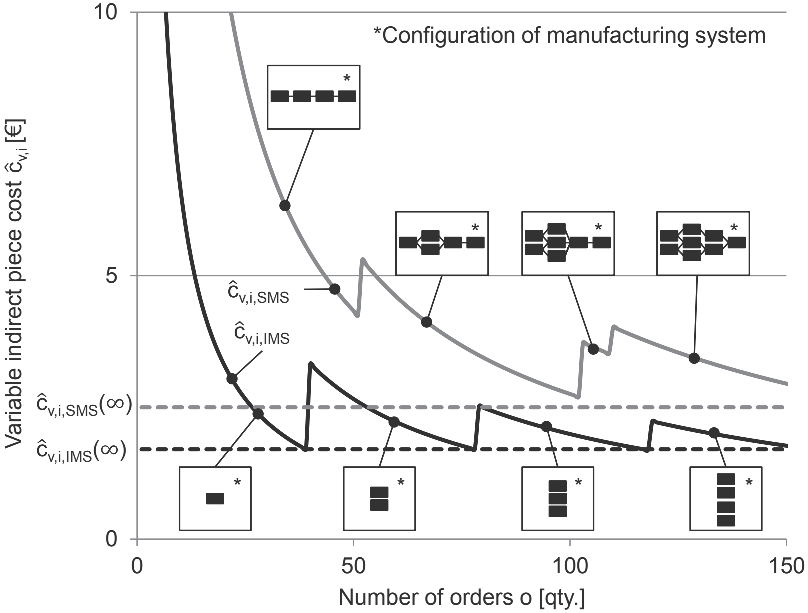


Figure 9.9: Progression of variable indirect piece cost over number of orders
Verlauf der variablen indirekten Stückkosten über der Anzahl der Aufträge

Figure 9.10 depicts the progression of throughput time over the number of orders o to be machined under the assumption of exponentially distributed interarrival times of orders and a transportation time t_{tr} = 5 min between the four machines of the segregated manufacturing system. Although the operation time of the integrated manufacturing system ($t_{op,IMS}$ = 195 min) is significantly smaller than the cumulated operation time of the segregated manufacturing system ($t_{op,SMS}$ = 345 min) a region exists in which the throughput time of the integrated manufacturing system exceeds the throughput time of the segregated manufacturing system. This is because the mean utilization of one multi-technology platform and thus the risk for waiting increases more pronounced than the mean utilization of four single-technology machine tools. Beyond $o_{crit,IMS}$ multi-technology platforms are paralleled which reduces the mean utilization of the integrated manufacturing system successively. However, due to an unequal workload distribution between the single-technology machine tools the average utilization remains at a higher level within the segregated manufacturing system. Hence, a higher degree of waiting occurs within the segregated manufacturing system which causes higher throughput times beyond $o_{crit,IMS}$.

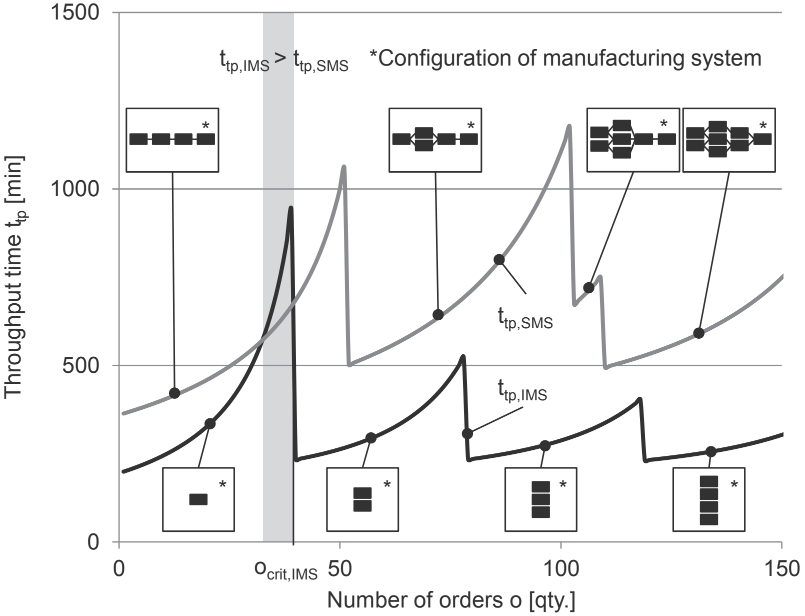


Figure 9.10: Progression of throughput time over number of orders

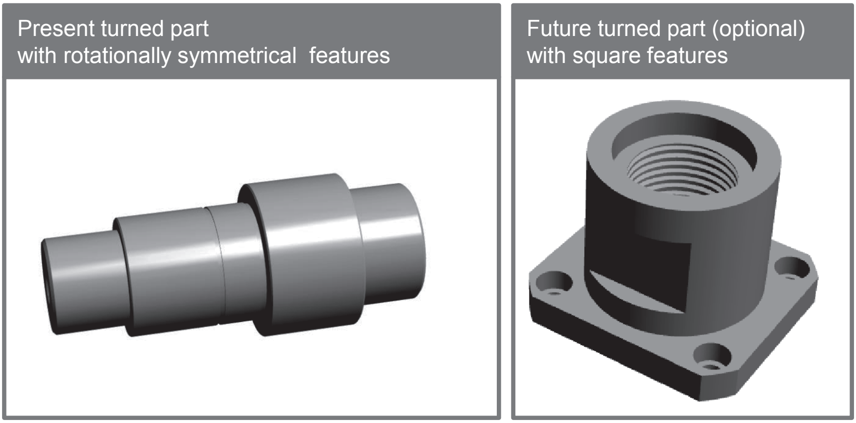
Verlauf der Durchlaufzeit über der Anzahl der Aufträge

Case study B shows that equipping a multi-technology platform with a second workspace may enhance productivity in comparison to a segregated manufacturing system. Furthermore, case study B illustrates that economic efficiency of manufacturing technology integration is not delimited to low output quantities. Depending on the productivity and cost of the segregated manufacturing system manufacturing technology integration may be successfully applied to high output quantities beyond the productivity limit of a single multi-technology platform $o_{crit,IMS}$.

9.3 Case study C: Turned parts with and without square features

A manufacturing enterprise has received a request to manufacture a turned part with exclusively rotationally symmetrical features depicted on the left side of figure 9.11. In the future, the enterprise might machine turned parts with square features as well, see right side of figure 9.11. However, the probability p is unkown that the enterprise actually receives an order for the turned part with square features.

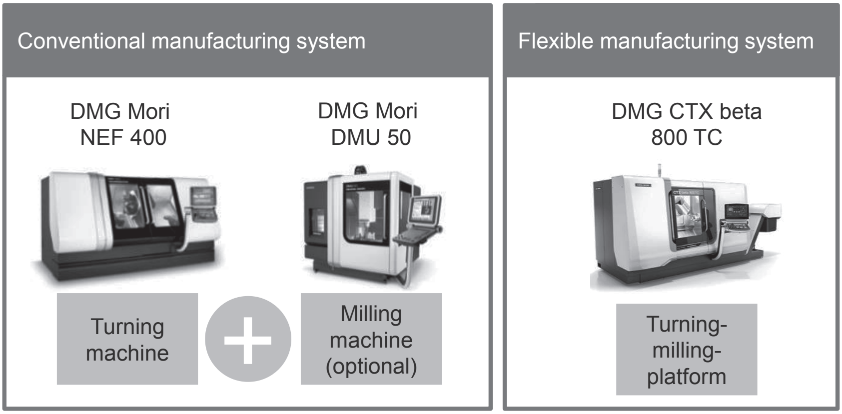
Two alternative strategies exist with regard to the configuration of the manufacturing system that will machine the parts in such volatile environment. Either the enterprise follows the strategy of conventional manufacturing or flexible manufacturing, compare chapter 8. Conventional manufacturing signifies that a turning machine is acquired at first to machine the present turned part and complemented by a milling machine in case the turned part with square features is ordered, see left side of figure 9.12. In case of flexible manufacturing a turning-milling-platform is acquired that may machine either turned part, see right side of figure 9.12.



Present turned part with rotationally symmetrical features

Future turned part (optional) with square features

Figure 9.11: Present part and future part (optional)
Gegenwärtiges Werkstück und zukünftiges Werkstück (optional)



Conventional manufacturing system

Flexible manufacturing system

Source of pictures: www.dmgmoriseiki.com

Figure 9.12: Machine tools of conventional and flexible manufacturing system
Werkzeugmaschinen des konventionellen und flexiblen Fertigungssystems

Conventional manufacturing brings about the advantage that costs are low if just the turned part with rotationally symmetrical features is demanded because a simple turning machine can be applied. However, acquisition of the additional milling machine in case the turned part with square features is required leads to additional cost ΔC_{conv} and a delayed availability of the conventional manufacturing system. This delayed availability reduces the contribution margin D achievable according to expression (8.6) because after some time the customer might choose another producer. The values for the time parameter λ and the maximum available time for amplification T_{max} as well as the ratio of additional cost to contribution margin $\Delta C_{conv}/D$ are to be found in table 9-6. The left side of figure 9.13 shows the drop-off of contribution margin D over the amplification period t.

The advantage of the flexible manufacturing system is that all functions are immediately available in case the turned part with square features is demanded. However, acquisition of a turning-milling-platform stipulates to spend the additional cost ΔC_{flex} in comparison to a conventional turning machine. The ratio of additional cost to contribution margin D is depicted in table 9-6.

Table 9-6: Parameters of efficiency calculation

Time parameter λ [days]	Maximum available time for amplification T_{max} [days]	Ratio $\Delta C_{conv}/D$ [-]	Ratio $\Delta C_{flex}/D$ [-]
10	100	0,25	0,2

The relative efficiency of conventional and flexible manufacturing depends on the probability p that parts with square features are demanded and the duration of the amplification period t to acquire a milling machine for the conventional manufacturing system. The isoquant $\Pi(t)$ which is determined according to expression (8.11) depicts all points of equal advantageousness of conventional and flexible manufacturing. It divides the plane spanned by probability p and amplification period t into a region in which conventional manufacturing is efficient and a region in which flexible manufacturing is efficient, see right side of figure 9.13.

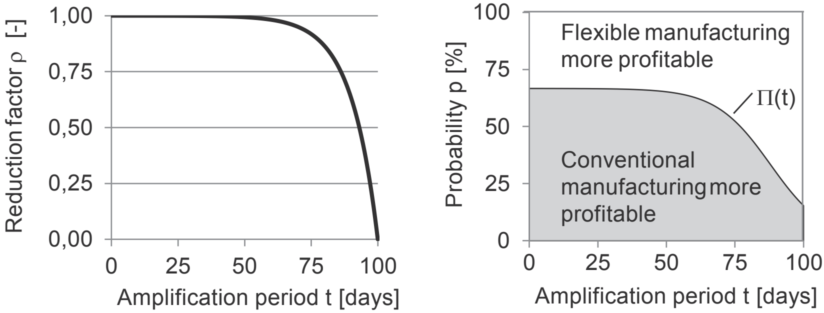


Figure 9.13: Reduction factor and probability over amplification period

Reduzierungsfaktor und Wahrscheinlichkeit über der Erweiterungsperiode

Conventional manufacturing is advantageous if the probability p is low that parts with square features are to be manufactured and the amplification period t to integrate a milling machine into the conventional manufacturing system is short. On the contrary, flexible manufacturing by a turning-milling-platform is advisable if it is almost certain that parts with square features are demanded and amplification of the conventional manufacturing system on short notice is impossible.

9.4 Interim conclusion

The recent chapter 9 illustrates the practical applicability to assess the relative profitability and the throughput times of an integrated manufacturing system in comparison to an segregated manufacturing system by the models presented in this thesis. Case A shows that the hurdle for relative profitability of integrated manufacturing is smaller for low output quantities. However, this does not signify that integrated manufacturing systems may not be competitive in a domain of high output quantities as can be seen by case B.

Case A and case B demonstrate that the shortening of the logistic chain through manufacturing technology integration does not necessarily account for shorter throughput times. A risk of higher throughput times exists in particular if a serial chain of unparalleled single-technology machine tools is substituted by a single multi-technology platform. This is on the grounds that utilization of the multi-technology platform is higher than the utilization of segregated manufacturing system which causes orders to wait in front of the multi-technology platform.

Case study C shows that the a priori integration of additional functions into multi-technology platforms should be considered, if the probability p is high that those functions are actually applied. Furthermore, the additional flexibility is advantageous in highly volatile markets in which an ex post amplification of the functional spectrum leads to a significant loss of market share.

10 Summary and Outlook

10.1 Summary

Manufacturing enterprises are exposed to highly competitive global markets. Such conditions promote an intensive search for adequate manufacturing system design paradigms. Manufacturing system design paradigms evolve over time through complication or through performance enhancing simplification of physically available production resources. Manufacturing technology integration is a manufacturing system design paradigm that *increases* the functional complexity of machine tools. The increasing functional complexity of machine tools must be justified through the notion of fitness attributed to manufacturing technology integration which is created by technology actors.

The analysis in the state of the art showed that the current notion of fitness of manufacturing technology integration is based on the machine hour rate calculation. However, the machine hour rate calculation does not consider the configuration change that may occur if a segregated manufacturing system is substituted by an integrated manufacturing system. Furthermore, output quantities are neglected. Therefore, the machine hour rate calculation is inappropriate to support decision making in the scope of manufacturing technology integration systematically. As a consequence, the market potential of manufacturing technology integration may not be exploited to its full extent.

The goal of this thesis was to predict the conditions under which integrated manufacturing systems are economically efficient in comparison to segregated manufacturing systems by models based on production, cost, and queuing theory, and thus create an alternative notion of fitness of manufacturing technology integration. Three efficiency criteria were considered: productivity, profitability, and throughput time. The analysis took place for single and double workspace multi-technology platforms. Furthermore, the propitiousness of a flexible manufacturing strategy in comparison to a conventional manufacturing strategy was elucidated.

Multi-technology platforms possess the same functional spectrum like a serial line of single-technology machine tools. However, multiple workpieces may be machined simultaneously within the workspaces of the segregated manufacturing system whereas only a single workpiece may be processed on a single workspace multi-technology platform. In other words, the serial line of single-technology machine tools possesses a higher productivity than a single workspace multi-technology platform. Thus, multi-technology platforms need to be paralleled such that the integrated manufacturing system is as productive as the segregated manufacturing system.

Integrated manufacturing systems are more profitable than segregated manufacturing systems if the piece cost of the integrated manufacturing system are smaller. The piece cost of the integrated and the segregated manufacturing system depend on the number of paralleled machine tools required to produce the desired output quantities. For low output quantities, a single multi-technology platform may substitute a segregated manufacturing system. Here, the integrated manufacturing system yields smaller cost if the cost of a single multi-technology platform is smaller than the cumulated cost of the serial line of single-technology machine tools, compare expression (6.68). For high output quantities the integrated manufacturing system is more profitable if the cost related to the critical output of a multi-technology platform undercuts the cumulated cost related to the critical output of the segregated manufacturing system, compare expression (6.69). This signifies that the hurdle for relative profitability of integrated manufacturing systems is lower for low output quantities than for high output quantities. Hence, manufacturing technology integration should be considered in particular if low output quantities are to be produced.

Manufacturing technology integration shortens the logistic chain within the plant since no transportation between machine tools is required. Although the logistic chain is shorter, throughput times might be higher in particular for low output quantities where a single multi-technology platform suffices to substitute a segregated manufacturing system. This is on the grounds that mean utilization of the single workspace multi-technology platform is higher than the mean utilization of the single-technology machine tools of the segregated manufacturing system. As a consequence, a large likelihood prevails that orders have to wait in front of the multi-technology platform while previous orders are still being processed whereas the likelihood of waiting is significantly smaller within the segregated manufacturing system.

Double workspace multi-technology platforms for parallel machining are equipped with technology resources that may travel between the workspaces. Depending on the type of workpieces to be machined the sharing of technology resources between the workspaces may enhance the productivity of integrated manufacturing systems significantly, however, at an elevated system cost. Therefore, the additional productivity must be pondered over the additional system cost. Two configurations of double workspace multi-technology platforms were assessed. The analysis of productivity, profitability, and throughput time showed that it is beneficial to install two fixed technology resources of type 1 in either workspace while technology resource 2 may travel between the workspaces.

Two alternative strategies exist to address changing functional requirements over the course of time. Flexible manufacturing signifies that the functional spectrum of multi-technology platforms is maximized a priori. However, flexible manufacturing increases the initial cost of the manufacturing system. For conventional manufacturing the functional window of the manufacturing system is adjusted to the initial functional requirements. If the functional requirements change over the course of time additional functions are integrated through acquisition of single-technology machine tools. The strategy of flexible manufacturing is more profitable than conventional manufacturing if the probability is high that the additional functions are actually applied during the reference period and the integration of functions causes less cost than the integration of an additional single-technology machine tool. This signifies that those functions should be integrated into a multi-technology platform that are likely to be used during its utilization phase.

10.2 Outlook

The economic efficiency of manufacturing technology integration was evaluated based on a decision-theoretical research approach. For this, quantitative models based on production, cost, and queuing theory were applied and discussed. Those models neglect human behavior. But, a manufacturing system is a sociotechnical system in which humans play a decisive role.

The influence of human behavior on the success of manufacturing technology integration is not captured by the quantitative models applied in this thesis. However, it must be expected that such an influence exists since the degree of human interaction differs between an integrated and a segregated manufacturing system. For example, fewer material handling and machine operation steps are carried out by humans within the integrated manufacturing system. This signifies that human errors are more likely to affect productivity, profitability, and throughput times within the segregated manufacturing system.

Future research should study the influence of human behavior on productivity, profitability, and throughput times of an integrated manufacturing system in comparison to a segregated manufacturing system. However, instead of a decision-theoretical research approach based on quantitative models a system-theoretical research approach based on field studies should be applied. This would signify, for example, that a manufacturing system is studied before and after multi-technology platforms are introduced to observe the effects of human behavior on the success of manufacturing technology integration.

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12 Appendix

12.1 Mathematical conversions

12.1.1 Variable piece cost of an integrated manufacturing system

Assumptions:

1. $C_{IMS}(x)=C_f(x)+C_{v,i,IMS}(x)+c_{v,d,IMS}\cdot x$
2. $C_{v,i,IMS}(x)=L_{para,IMS}\cdot c_{v,i,IMS}$
3. $L_{para,IMS}(x)=\text{ceil}\left(\frac{x}{x_{crit,l}}\right)$

Theorem:

$$\hat{c}_{v,i,IMS}(\infty)=\lim_{x\to\infty}\frac{C_{v,i,IMS}(x)}{x}=\frac{c_{v,i,IMS}}{x_{crit,l}}$$

Proof:

$$\hat{c}_{v,i,IMS}(\infty)=\lim_{x\to\infty}\left[\frac{C_{v,i,IMS}(x)}{x}\right]=\lim_{x\to\infty}\left[\frac{L_{para,IMS}(x)\cdot c_{v,i,IMS}}{x}\right]$$

$$=c_{v,i,IMS}\cdot\lim_{x\to\infty}\left[\frac{L_{para,IMS}(x)}{x}\right]$$

$$\overset{*}{\widehat{=}}\frac{c_{v,i,IMS}}{x_{crit,IMS}}$$

*Auxiliary consideration:

$$\lim_{x\to\infty}\left[\frac{L_{para,IMS}(x)}{x}\right]=\lim_{x\to\infty}\left[\frac{\text{ceil}\left(\frac{x}{x_{crit,IMS}}\right)}{x}\right]=\lim_{i\to\infty}\left[\frac{\text{ceil}\left(\frac{i\cdot x_{crit,IMS}}{x_{crit,IMS}}\right)}{i\cdot x_{crit,IMS}}\right]\text{, with } x=i\cdot x_{crit,IMS},\ i\in\mathbb{Q}^+$$

$$=\lim_{i\to\infty}\left[\frac{\text{ceil}(i)}{i\cdot x_{crit,IMS}}\right]=\frac{1}{x_{crit,IMS}}$$

12.1.2 Variable piece cost of a segregated manufacturing system

Assumptions:

1. $C_{SMS}(x)=C_f(x)+C_{v,i,SMS}(x)+c_{v,d,SMS}\cdot x$
2. $C_{v,i,SMS}(x)=\sum_{l=1}^{L_{serial,SMS}}L_{para,l}(x)\cdot c_{v,i,SMS,l}$
3. $L_{para,l}(x)=\text{ceil}\left(\frac{x}{x_{crit,l}}\right)$

Theorem:

$$\hat{c}_{v,i,SMS}(\infty)=\lim_{x\to\infty}\frac{C_{v,i,SMS}(x)}{x}=\sum_{l=1}^{L_{serial,SMS}}\frac{c_{v,i,SMS,l}}{x_{crit,l}}$$

Proof:

$$\hat{c}_{v,i,SMS}(\infty)=\lim_{x\to\infty}\left[\frac{C_{v,i,SMS}(x)}{x}\right]=\lim_{x\to\infty}\left[\frac{\sum_{l=1}^{L_{serial,SMS}} L_{para,l}(x)\cdot c_{v,i,SMS,l}}{x}\right]$$

$$=\sum_{l=1}^{L_{serial,SMS}}\left(c_{v,i,SMS,l}\cdot\lim_{x\to\infty}\left[\frac{L_{para,l}(x)}{x}\right]\right)$$

$$\overset{*}{\widehat{=}}\sum_{l=1}^{L_{serial,SMS}}\frac{c_{v,i,SMS,l}}{x_{crit,l}}$$

*Auxiliary consideration:

$$\lim_{x\to\infty}\left[\frac{L_{para,l}(x)}{x}\right]=\lim_{x\to\infty}\left[\frac{\mathrm{ceil}\left(\frac{x}{x_{crit,l}}\right)}{x}\right]=\lim_{i\to\infty}\left[\frac{\mathrm{ceil}\left(\frac{i\cdot x_{crit,l}}{x_{crit,l}}\right)}{i\cdot x_{crit,l}}\right],\text{ with } x=i\cdot x_{crit,l},\ i\in Q^{+}$$

$$=\lim_{i\to\infty}\left[\frac{\mathrm{ceil}(i)}{i\cdot x_{crit,l}}\right]=\frac{1}{x_{crit,l}}$$

12.1.3 Operation time ratio for two machines

$$\tau_{op} = 1/6\cdot(72\cdot U_{m,max}\cdot f_1^{2}\cdot\tau_{tr,SMS} - 72\cdot U_{m,max}\cdot f_1\cdot\tau_{tr,SMS} - 84\cdot\tau_{tr,SMS}^{2}\cdot U_{m,max} + 24\cdot\tau_{tr,SMS}^{2} + 96\cdot\tau_{tr,SMS}^{2}\cdot U_{m,max}^{2} + 24\cdot\tau_{tr,SMS}^{3}\cdot U_{m,max}^{2} - 24\cdot\tau_{tr,SMS}^{3}\cdot U_{m,max} - 36\cdot\tau_{tr,SMS}^{2}\cdot U_{m,max}^{3} - 8\cdot\tau_{tr,SMS}^{3}\cdot U_{m,max}^{3} - 60\cdot\tau_{tr,SMS}\cdot U_{m,max} + 36\cdot\tau_{tr,SMS}\cdot U_{m,max}^{2} - 144\cdot\tau_{tr,SMS}\cdot U_{m,max}^{3}\cdot f_1 + 144\cdot\tau_{tr,SMS}\cdot U_{m,max}^{3}\cdot f_1^{2} + 216\cdot\tau_{tr,SMS}\cdot U_{m,max}^{2}\cdot f_1 - 216\cdot\tau_{tr,SMS}\cdot U_{m,max}^{2}\cdot f_1^{2} + 8\cdot\tau_{tr,SMS}^{3} - 72\cdot U_{m,max}\cdot f_1 + 24\cdot\tau_{tr,SMS} + 72\cdot U_{m,max}\cdot f_1^{2} + 36\cdot U_{m,max}^{2}\cdot f_1 - 36\cdot U_{m,max}^{2}\cdot f_1^{2} + 8 + 12\cdot \mathrm{sqrt}(-6\cdot U_{m,max}^{4}\cdot f_1\cdot\tau_{tr,SMS} - 150\cdot U_{m,max}^{4}\cdot f_1^{2}\cdot\tau_{tr,SMS} + 48\cdot U_{m,max}^{6}\cdot f_1\cdot\tau_{tr,SMS}^{3} - 36\cdot U_{m,max}^{6}\cdot f_1\cdot\tau_{tr,SMS}^{2} - 36\cdot U_{m,max}^{6}\cdot f_1^{2}\cdot\tau_{tr,SMS} + 72\cdot U_{m,max}^{4}\cdot f_1\cdot\tau_{tr,SMS}^{4} - 48\cdot U_{m,max}^{5}\cdot f_1\cdot\tau_{tr,SMS}^{4} - 48\cdot U_{m,max}^{3}\cdot f_1\cdot\tau_{tr,SMS}^{4} + 12\cdot U_{m,max}^{2}\cdot f_1\cdot\tau_{tr,SMS}^{4} - 168\cdot U_{m,max}^{5}\cdot f_1\cdot\tau_{tr,SMS}^{3} + 102\cdot U_{m,max}^{5}\cdot f_1\cdot\tau_{tr,SMS}^{2} + 216\cdot U_{m,max}^{4}\cdot f_1\cdot\tau_{tr,SMS}^{3} + 24\cdot U_{m,max}^{2}\cdot f_1\cdot\tau_{tr,SMS}^{3} - 120\cdot U_{m,max}^{3}\cdot f_1\cdot\tau_{tr,SMS}^{3} + 48\cdot U_{m,max}^{2}\cdot f_1^{3}\cdot\tau_{tr,SMS} + 132\cdot U_{m,max}^{5}\cdot f_1^{2}\cdot\tau_{tr,SMS} + 24\cdot U_{m,max}^{2}\cdot f_1^{3}\cdot\tau_{tr,SMS}^{2} + 48\cdot U_{m,max}^{5}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{4} - 12\cdot U_{m,max}^{6}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{4} - 24\cdot U_{m,max}^{2}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{3} - 72\cdot U_{m,max}^{4}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{4} + 48\cdot U_{m,max}^{3}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{4} + 312\cdot U_{m,max}^{4}\cdot f_1^{4}\cdot\tau_{tr,SMS}^{2} - 624\cdot U_{m,max}^{4}\cdot f_1^{3}\cdot\tau_{tr,SMS}^{2} + 132\cdot U_{m,max}^{6}\cdot f_1^{4}\cdot\tau_{tr,SMS}^{2} - 264\cdot U_{m,max}^{6}\cdot f_1^{3}\cdot\tau_{tr,SMS}^{2} - 360\cdot U_{m,max}^{5}\cdot f_1^{4}\cdot\tau_{tr,SMS}^{2} + 720\cdot U_{m,max}^{5}\cdot f_1^{3}\cdot\tau_{tr,SMS}^{2} - 48\cdot U_{m,max}^{6}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{3} + 168\cdot U_{m,max}^{6}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{2} - 156\cdot U_{m,max}^{4}\cdot f_1^{4}\cdot\tau_{tr,SMS} + 312\cdot U_{m,max}^{4}\cdot f_1^{3}\cdot\tau_{tr,SMS} + 132\cdot U_{m,max}^{5}\cdot f_1^{4}\cdot\tau_{tr,SMS} - 264\cdot U_{m,max}^{5}\cdot f_1^{3}\cdot\tau_{tr,SMS} + 168\cdot U_{m,max}^{5}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{3} - 462\cdot U_{m,max}^{5}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{2} + 120\cdot U_{m,max}^{3}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{3} - 216\cdot U_{m,max}^{4}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{3} - 12\cdot U_{m,max}^{2}\cdot f_1^{2}\cdot\tau_{tr,SMS}^{4} - 168\cdot U_{m,max}^{3}\cdot f_1^{3}\cdot\tau_{tr,SMS} + 84\cdot U_{m,max}^{3}\cdot f_1^{4}\cdot\tau_{tr,SMS} - 36\cdot U_{m,max}^{6}\cdot f_1^{4}\cdot\tau_{tr,SMS} + 144\cdot U_{m,max}^{3}\cdot f_1^{3}\cdot\tau_{tr,SMS}^{2} + 72\cdot U_{m,max}^{6}\cdot f_1^{3}\cdot\tau_{tr,SMS} - 72\cdot U_{m,max}^{3}\cdot f_1^{4}\cdot\tau_{tr,SMS}^{2} + 12\cdot U_{m,max}^{6}\cdot f_1\cdot\tau_{tr,SMS}^{4} + 42\cdot\tau_{tr,SMS}^{3}\cdot U_{m,max}^{5} + 12\cdot\tau_{tr,SMS}^{4}\cdot U_{m,max}^{5} - 3\cdot\tau_{tr,SMS}^{2}\cdot U_{m,max}^{2} - 6\cdot\tau_{tr,SMS}^{3}\cdot U_{m,max}^{2} - 3\cdot\tau_{tr,SMS}^{4}\cdot U_{m,max}^{6} - 12\cdot\tau_{tr,SMS}^{3}\cdot U_{m,max}^{6} - 24\cdot U_{m,max}^{2}\cdot f_1^{4}\cdot\tau_{tr,SMS} + 6\cdot\tau_{tr,SMS}^{2}\cdot U_{m,max}^{3} - 12\cdot U_{m,max}^{2}\cdot f_1^{4}\cdot\tau_{tr,SMS}^{2} + 30\cdot\tau_{tr,SMS}^{3}\cdot U_{m,max}^{3} + 12\cdot U_{m,max}^{3}\cdot f_1^{2} -$$

$216 \cdot U_{m,max}^5 \cdot f_1^4 + 6 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1 + 78 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1^2 - 24 \cdot \tau_{tr,SMS} \cdot$ $U_{m,max}^2 \cdot f_1^2 - 3 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 - 54 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^4 + 6 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1 - 78 \cdot$ $\tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1^2 - 84 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1 + 396 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1^2 + 12 \cdot$ $\tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1 - 24 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1^2 - 3 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^2 - 18 \cdot \tau_{tr,SMS}^4 \cdot$ $U_{m,max}^4 + 12 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^3 - 12 \cdot U_{m,max}^2 \cdot f_1^2 + 72 \cdot U_{m,max}^3 \cdot f_1^3 + 24 \cdot U_{m,max}^2 \cdot f_1^3 +$ $429 \cdot U_{m,max}^4 \cdot f_1^4 - 13 \cdot U_{m,max}^4 \cdot f_1^3 - 276 \cdot U_{m,max}^3 \cdot f_1^4 - 3 \cdot U_{m,max}^4 \cdot f_1^2 - 12 \cdot U_{m,max}^2$ $\cdot f_1^4 + 216 \cdot U_{m,max}^5 \cdot f_1^5 - 432 \cdot U_{m,max}^4 \cdot f_1^5 + 12 \cdot U_{m,max}^6 \cdot f_1^6 - 36 \cdot U_{m,max}^6 \cdot f_1^5 -72 \cdot$ $U_{m,max}^5 \cdot f_1^6 + 36 \cdot U_{m,max}^6 \cdot f_1^4 + 144 \cdot U_{m,max}^4 \cdot f_1^6 + 72 \cdot U_{m,max}^5 \cdot f_1^3 + 288 \bullet U_{m,max}^3 \cdot$ $f_1^5 - 12 \cdot U_{m,max}^6 \cdot f_1^3 - 96 \cdot U_{m,max}^3 \cdot f_1^6))^{1/3} - 6 \cdot (1/3 \cdot U_{m,max}^2 \cdot f_1^2 + 2/3 \cdot U_{m,max} \cdot f_1 -$ $1/3 \cdot U_{m,max}^2 \cdot f_1 + 5/9 \cdot \tau_{tr,SMS} \cdot U_{m,max} - 1/3 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 - 2/3 \cdot U_{m,max} \cdot f_1^2 - 1/9 \cdot$ $\tau_{tr,SMS}^2 - 2/9 \cdot \tau_{tr,SMS} + 2/9 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max} - 1/9 - 1/9 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2)/((72 \cdot U_{m,max} \cdot$ $f_1^2 \cdot \tau_{tr,SMS} - 72 \cdot U_{m,max} \cdot f_1 \cdot \tau_{tr,SMS} - 84 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max} + 24 \cdot \tau_{tr,SMS}^2 + 96 \cdot \tau_{tr,SMS}^2 \cdot$ $U_{m,max}^2 + 24 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 - 24 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max} - 36 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 - 8 \cdot \tau_{tr,SMS}^3$ $\cdot U_{m,max}^3 - 60 \cdot \tau_{tr,SMS} \cdot U_{m,max} + 36 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 - 144 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1 + 144 \cdot$ $\tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1^2 + 216 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1 - 216 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1^2 + 8 \cdot \tau_{tr,SMS}^3 -$ $72 \cdot U_{m,max} \cdot f_1 + 24 \cdot \tau_{tr,SMS} + 72 \cdot U_{m,max} \cdot f_1^2 + 36 \cdot U_{m,max}^2 \cdot f_1 - 36 \cdot U_{m,max}^2 \cdot f_1^2 + 8 +$ $12 \cdot \mathrm{sqrt}(-6 \cdot U_{m,max}^4 \cdot f_1 \cdot \tau_{tr,SMS} - 150 \cdot U_{m,max}^4 \cdot f_1^2 \cdot \tau_{tr,SMS} + 48 \cdot U_{m,max}^6 \cdot f_1 \cdot \tau_{tr,SMS}^3 -$ $36 \cdot U_{m,max}^6 \cdot f_1 \cdot \tau_{tr,SMS}^2 - 36 \cdot U_{m,max}^6 \cdot f_1^2 \cdot \tau_{tr,SMS} + 72 \cdot U_{m,max}^4 \cdot f_1 \cdot \tau_{tr,SMS}^4 - 48 \cdot$ $U_{m,max}^5 \cdot f_1 \cdot \tau_{tr,SMS}^4 - 48 \cdot U_{m,max}^3 \cdot f_1 \cdot \tau_{tr,SMS}^4 + 12 \cdot U_{m,max}^2 \cdot f_1 \cdot \tau_{tr,SMS}^4 - 168 \cdot U_{m,max}^5$ $\cdot f_1 \cdot \tau_{tr,SMS}^3 + 102 \cdot U_{m,max}^5 \cdot f_1 \cdot \tau_{tr,SMS}^2 + 216 \cdot U_{m,max}^4 \cdot f_1 \cdot \tau_{tr,SMS}^3 + 24 \cdot U_{m,max}^2 \cdot f_1 \cdot$ $\tau_{tr,SMS}^3 - 120 \cdot U_{m,max}^3 \cdot f_1 \cdot \tau_{tr,SMS}^3 + 48 \cdot U_{m,max}^2 \cdot f_1^3 \cdot \tau_{tr,SMS} + 132 \cdot U_{m,max}^5 \cdot f_1^2 \cdot \tau_{tr,SMS}$ $+ 24 \cdot U_{m,max}^2 \cdot f_1^3 \cdot \tau_{tr,SMS}^2 + 48 \cdot U_{m,max}^5 \cdot f_1^2 \cdot \tau_{tr,SMS}^4 - 12 \cdot U_{m,max}^6 \cdot f_1^2 \cdot \tau_{tr,SMS}^4 - 24 \cdot$ $U_{m,max}^2 \cdot f_1^2 \cdot \tau_{tr,SMS}^3 - 72 \cdot U_{m,max}^4 \cdot f_1^2 \cdot \tau_{tr,SMS}^4 + 48 \cdot U_{m,max}^3 \cdot f_1^2 \cdot \tau_{tr,SMS}^4 + 312 \cdot$ $U_{m,max}^4 \cdot f_1^4 \cdot \tau_{tr,SMS}^2 - 624 \cdot U_{m,max}^4 \cdot f_1^3 \cdot \tau_{tr,SMS}^2 + 132 \cdot U_{m,max}^6 \cdot f_1^4 \cdot \tau_{tr,SMS}^2 - 264 \cdot$ $U_{m,max}^6 \cdot f_1^3 \cdot \tau_{tr,SMS}^2 - 360 \cdot U_{m,max}^5 \cdot f_1^4 \cdot \tau_{tr,SMS}^2 + 720 \cdot U_{m,max}^5 \cdot f_1^3 \cdot \tau_{tr,SMS}^2 - 48 \cdot$ $U_{m,max}^6 \cdot f_1^2 \cdot \tau_{tr,SMS}^3 + 168 \cdot U_{m,max}^6 \cdot f_1^2 \cdot \tau_{tr,SMS}^2 - 156 \cdot U_{m,max}^4 \cdot f_1^4 \cdot \tau_{tr,SMS} + 312 \cdot$ $U_{m,max}^4 \cdot f_1^3 \cdot \tau_{tr,SMS} + 132 \cdot U_{m,max}^5 \cdot f_1^4 \cdot \tau_{tr,SMS} -264 \cdot U_{m,max}^5 \cdot f_1^3 \cdot \tau_{tr,SMS} + 168 \cdot$ $U_{m,max}^5 \cdot f_1^2 \cdot \tau_{tr,SMS}^3 - 462 \cdot U_{m,max}^5 \cdot f_1^2 \cdot \tau_{tr,SMS}^2 + 120 \cdot U_{m,max}^3 \cdot f_1^2 \cdot \tau_{tr,SMS}^3 - 216 \cdot$ $U_{m,max}^4 \cdot f_1^2 \cdot \tau_{tr,SMS}^3 - 12 \cdot U_{m,max}^2 \cdot f_1^2 \cdot \tau_{tr,SMS}^4 - 168 \cdot U_{m,max}^3 \cdot f_1^3 \cdot \tau_{tr,SMS} + 84 \cdot$ $U_{m,max}^3 \cdot f_1^4 \cdot \tau_{tr,SMS} - 36 \cdot U_{m,max}^6 \cdot f_1^4 \cdot \tau_{tr,SMS} + 144 \cdot U_{m,max}^3 \cdot f_1^3 \cdot \tau_{tr,SMS}^2 + 72 \cdot U_{m,max}^6$ $\cdot f_1^3 \cdot \tau_{tr,SMS} - 72 \cdot U_{m,max}^3 \cdot f_1^4 \cdot \tau_{tr,SMS}^2 + 12 \cdot U_{m,max}^6 \cdot f_1 \cdot \tau_{tr,SMS}^4 + 42 \cdot t_{tr,SMS}^3 \cdot U_{m,max}^5$ $+ 12 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^5 - 3 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 - 6 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 - 3 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^6$ $- 12 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^6 - 24 \cdot U_{m,max}^2 \cdot f_1^4 \cdot \tau_{tr,SMS} + 6 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 - 12 \cdot U_{m,max}^2 \cdot$ $f_1^4 \cdot \tau_{tr,SMS}^2 + 30 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^3 + 12 \cdot U_{m,max}^3 \cdot f_1^2 - 216 \cdot U_{m,max}^5 \cdot f_1^4 + 6 \cdot \tau_{tr,SMS} \cdot$ $U_{m,max}^3 \cdot f_1 + 78 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1^2 - 24 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1^2 - 3 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 -$ $54 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^4 + 6 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1 - 78 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1^2 - 84 \cdot \tau_{tr,SMS}^2 \cdot$ $U_{m,max}^4 \cdot f_1 + 396 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1^2 + 12 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1 - 24 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2$ $\cdot f_1^2 - 3 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^2 - 18 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^4 + 12 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^3 - 12 \cdot U_{m,max}^2 \cdot$ $f_1^2 + 72 \cdot U_{m,max}^3 \cdot f_1^3 + 24 \cdot U_{m,max}^2 \cdot f_1^3 + 429 \cdot U_{m,max}^4 \cdot f_1^4 - 138 \cdot U_{m,max}^4 \cdot f_1^3 - 276 \cdot$ $U_{m,max}^3 \cdot f_1^4 - 3 \cdot U_{m,max}^4 \cdot f_1^2 - 12 \cdot U_{m,max}^2 \cdot f_1^4 + 216 \cdot U_{m,max}^5 \cdot f_1^5 - 432 \cdot U_{m,max}^4 \cdot f_1^5$ $+ 12 \cdot U_{m,max}^6 \cdot f_1^6 - 36 \cdot U_{m,max}^6 \cdot f_1^5 - 72 \cdot U_{m,max}^5 \cdot f_1^6 + 36 \cdot U_{m,max}^6 \cdot f_1^4 + 144 \cdot$

$U_{m,max}^4 \cdot f_1^6 + 72 \cdot U_{m,max}^5 \cdot f_1^3 + 288 \cdot U_{m,max}^3 \cdot f_1^5 - 12 \cdot U_{m,max}^6 \cdot f_1^3 - 96 \cdot U_{m,max}^3 \cdot$ $f_1^6))^{1/3} + 1/3 \cdot \tau_{tr,SMS} + 1/3 - 1/3 \cdot t_{tr,SMS} \cdot U_{m,max}$

12.1.4 Operation time ratio for three machines

$\tau_{op} = 1/6 \cdot (8 - 6 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1 + 126 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1 - 6 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max} \cdot$ $f_1 + 12 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1 - 48 \cdot \tau_{tr,SMS} \cdot U_{m,max} \cdot f_1 - 15 \cdot U_{m,max}^3 \cdot f_1 - 78 \cdot \tau_{tr,SMS} \cdot$ $U_{m,max}^3 \cdot f_1 + 33 \cdot U_{m,max}^3 \cdot f_1^2 + 93 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1^2 - 147 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1^2 + 54$ $\cdot U_{m,max} \cdot f_1^2 \cdot \tau_{tr,SMS} + 3 \cdot \mathrm{sqrt}(1188 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^4 \cdot f_1 + 168 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 \cdot f_1 -$ $732 \cdot t_{tr,SMS}^3 \cdot U_{m,max}^3 \cdot f_1 - 648 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^4 \cdot f_1^2 - 348 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1 - 1980$ $\cdot t_{tr,SMS}^3 \cdot U_{m,max}^4 \cdot f_1^2 + 24 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1 + 432 \cdot U_{m,max}^4 \cdot f_1^3 \cdot \tau_{tr,SMS} + 504 \cdot \tau_{tr,SMS}$ $\cdot U_{m,max}^2 \cdot f_1^3 - 2304 \cdot U_{m,max}^5 \cdot f_1^4 \cdot \tau_{tr,SMS} - 144 \cdot U_{m,max}^6 \cdot f_1^3 \cdot \tau_{tr,SMS} - 144 \cdot U_{m,max}^6 \cdot$ $f_1^2 \cdot \tau_{tr,SMS} + 2196 \cdot U_{m,max}^4 \cdot f_1^4 \cdot \tau_{tr,SMS} + 720 \cdot U_{m,max}^6 \cdot f_1^4 \cdot \tau_{tr,SMS} + 324 \cdot \tau_{tr,SMS}^2 \cdot$ $U_{m,max}^4 \cdot f_1 + 360 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1^3 + 120 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1 + 837 \cdot \tau_{tr,SMS}^2 \cdot$ $U_{m,max}^6 \cdot f_1^4 - 432 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1^4 - 108 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^2 \cdot f_1^2 + 72 \cdot \tau_{tr,SMS}^3 \cdot$ $U_{m,max}^2 \cdot f_1^3 + 30 \cdot \tau_{tr,SMS} \cdot U_{m,max}^4 \cdot f_1 + 432 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^3 \cdot f_1^2 - 348 \cdot \tau_{tr,SMS}^3 \cdot$ $U_{m,max}^6 \cdot f_1^2 + 1284 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^3 \cdot f_1^2 + 72 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^2 \cdot f_1 - 312 \cdot \tau_{tr,SMS}^3 \cdot$ $U_{m,max}^2 \cdot f_1^2 - 48 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1 + 252 \cdot U_{m,max}^3 \cdot f_1^2 - 84 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 \cdot f_1 - 6 \cdot$ $\tau_{tr,SMS} \cdot U_{m,max}^5 \cdot f_1 - 12 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^6 \cdot f_1 + 228 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^6 \cdot f_1 - 288 \cdot \tau_{tr,SMS}^4 \cdot$ $U_{m,max}^3 \cdot f_1 - 852 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^5 \cdot f_1 - 288 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^5 \cdot f_1 + 432 \cdot \tau_{tr,SMS}^4 \cdot$ $U_{m,max}^4 \cdot f_1 + 72 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^6 \cdot f_1 - 2322 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 \cdot f_1^4 - 180 \cdot \tau_{tr,SMS}^2 \cdot$ $U_{m,max}^3 \cdot f_1^3 - 36 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^6 \cdot f_1^3 - 1836 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1^3 - 1116 \cdot \tau_{tr,SMS}^2 \cdot$ $U_{m,max}^6 \cdot f_1^3 + 108 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^4 \cdot f_1^3 + 36 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^5 \cdot f_1^3 + 2772 \cdot \tau_{tr,SMS}^2 \cdot$ $U_{m,max}^5 \cdot f_1^3 + 228 \cdot \tau_{tr,SMS} \cdot U_{m,max}^5 \cdot f_1^3 - 384 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 \cdot f_1^2 + 624 \cdot \tau_{tr,SMS} \cdot$ $U_{m,max}^5 \cdot f_1^2 - 432 \cdot U_{m,max}^6 \cdot f_1^5 \cdot \tau_{tr,SMS} - 108 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^6 \cdot f_1^2 + 1458 \cdot U_{m,max}^5 \cdot$ $f_1^5 \cdot \tau_{tr,SMS} - 396 \cdot U_{m,max}^3 \cdot f_1^4 \cdot \tau_{tr,SMS} + 924 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1^2 -1566 \cdot U_{m,max}^4 \cdot f_1^5 \cdot$ $\tau_{tr,SMS} + 294 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^6 \cdot f_1^2 - 180 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^3 \cdot f_1^3 + 1020 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3$ $\cdot f_1^2 - 408 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1^2 + 1356 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^5 \cdot f_1^2 - 1092 \cdot \tau_{tr,SMS} \cdot U_{m,max}^4 \cdot$ $f_1^2 - 312 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1^2 + 540 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1^5 - 522 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1^2 +$ $432 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^5 \cdot f_1^2 + 2025 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1^4 - 108 \cdot U_{m,max}^2 \cdot f_1^4 \cdot \tau_{tr,SMS}^2 -$ $1020 \cdot U_{m,max}^3 \cdot f_1^3 \cdot \tau_{tr,SMS} - 216 \cdot U_{m,max}^2 \cdot f_1^4 \cdot \tau_{tr,SMS} - 108 \cdot U_{m,max}^2 \cdot f_1^2 + 36 \cdot U_{m,max}^3$ $\cdot f_1^3 + 216 \cdot U_{m,max}^2 \cdot f_1^3 - 12 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 + 36 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 + 108 \cdot \tau_{tr,SMS}^3 \cdot$ $U_{m,max}^3 - 24 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 - 39 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 - 180 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^4 - 219 \cdot$ $U_{m,max}^4 \cdot f_1^2 - 660 \cdot U_{m,max}^4 \cdot f_1^3 + 3246 \cdot U_{m,max}^4 \cdot f_1^4 - 1476 \cdot U_{m,max}^3 \cdot f_1^4 - 108 \cdot$ $U_{m,max}^2 \cdot f_1^4 - 12 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^2 + 48 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^3 - 72 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^4 + 84 \cdot$ $U_{m,max}^5 \cdot f_1^2 + 576 \cdot U_{m,max}^5 \cdot f_1^3 - 2232 \cdot U_{m,max}^5 \cdot f_1^4 + 18 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 + 132 \cdot$ $\tau_{tr,SMS}^3 \cdot U_{m,max}^5 + 48 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^5 - 36 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^6 - 3 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^6 - 12$ $\cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^6 - 144 \cdot U_{m,max}^6 \cdot f_1^3 + 504 \cdot U_{m,max}^6 \cdot f_1^4 - 12 \cdot U_{m,max}^6 \cdot f_1^2 - 528 \cdot$ $U_{m,max}^6 \cdot f_1^5 + 2400 \cdot U_{m,max}^5 \cdot f_1^5 - 3636 \cdot U_{m,max}^4 \cdot f_1^5 + 180 \cdot U_{m,max}^6 \cdot f_1^6 - 828 \cdot$ $U_{m,max}^5 \cdot f_1^6 + 1269 \cdot U_{m,max}^4 \cdot f_1^6 + 1836 \cdot U_{m,max}^3 \cdot f_1^5 - 648 \cdot U_{m,max}^3 \cdot f_1^6) -12 \cdot U_{m,max}$ $+ 24 \cdot \tau_{tr,SMS} - 42 \cdot U_{m,max} \cdot f_1 + 51 \cdot U_{m,max}^2 \cdot f_1 - 84 \cdot U_{m,max}^2 \cdot f_1^2 + 54 \cdot U_{m,max} \cdot f_1^2 - 66$ $\cdot \tau_{tr,SMS} \cdot U_{m,max} + 57 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 - 17 \cdot U_{m,max}^3 \cdot f_1^3 + 27 \cdot U_{m,max}^2 \cdot f_1^3 + 6 \cdot$ $U_{m,max}^2 -78 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max} + 24 \cdot \tau_{tr,SMS}^2 - U_{m,max}^3 + 84 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 - 15 \cdot \tau_{tr,SMS} \cdot$

$$\begin{aligned}
&U_{m,max}^3 - 30 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 - 8 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^3 + 24 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 - 24 \cdot \tau_{tr,SMS}^3 \\
&\cdot U_{m,max} + 8 \cdot \tau_{tr,SMS}^3)^{1/3} - 6 \cdot (-1/18 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1 - 5/18 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 + ½ \cdot \\
&\tau_{tr,SMS} \cdot U_{m,max} + 1/18 \cdot \tau_{tr,SMS} \cdot U_{m,max} \cdot f_1 - 5/18 \cdot U_{m,max}^2 \cdot f_1 + 11/36 \cdot U_{m,max}^2 \cdot f_1^2 + \\
&7/18 \cdot U_{m,max} \cdot f_1 - ½ \cdot U_{m,max} \cdot f_1^2 - 1/9 + 1/9 \cdot U_{m,max} - 2/9 \cdot \tau_{tr,SMS} - 1/36 \cdot U_{m,max}^2 + 2/9 \cdot \\
&\tau_{tr,SMS}^2 \cdot U_{m,max} - 1/9 \cdot \tau_{tr,SMS}^2 - 1/9 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2)/((8 - 6 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1 + 126 \\
&\cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1 - 6 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max} \cdot f_1 + 12 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1 - 48 \cdot \tau_{tr,SMS} \cdot \\
&U_{m,max} \cdot f_1 - 15 \cdot U_{m,max}^3 \cdot f_1 - 78 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1 + 33 \cdot U_{m,max}^3 \cdot f_1^2 + 93 \cdot \tau_{tr,SMS} \cdot \\
&U_{m,max}^3 \cdot f_1^2 - 147 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1^2 + 54 \cdot U_{m,max} \cdot f_1^2 \cdot \tau_{tr,SMS} + 3 \cdot \mathrm{sqrt}(1188 \cdot \\
&\tau_{tr,SMS}^3 \cdot U_{m,max}^4 \cdot f_1 + 168 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 \cdot f_1 - 732 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^3 \cdot f_1 - 648 \cdot \\
&\tau_{tr,SMS}^4 \cdot U_{m,max}^4 \cdot f_1^2 - 348 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1 - 1980 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^4 \cdot f_1^4 + 24 \cdot \\
&\tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1 + 432 \cdot U_{m,max}^4 \cdot f_1^3 \cdot \tau_{tr,SMS} + 504 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot f_1^3 - 2304 \cdot \\
&U_{m,max}^5 \cdot f_1^4 \cdot \tau_{tr,SMS} - 144 \cdot U_{m,max}^6 \cdot f_1^3 \cdot \tau_{tr,SMS} - 144 \cdot U_{m,max}^6 \cdot f_1^2 \cdot \tau_{tr,SMS} + 2196 \cdot \\
&U_{m,max}^4 \cdot f_1^4 \cdot \tau_{tr,SMS} + 720 \cdot U_{m,max}^6 \cdot f_1^4 \cdot \tau_{tr,SMS} + 324 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1 + 360 \cdot \\
&\tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1^3 + 120 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot f_1 + 837 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^6 \cdot f_1^4 - 432 \cdot \\
&\tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1^4 - 108 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^2 \cdot f_1^2 + 72 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 \cdot f_1^3 + 30 \cdot \\
&\tau_{tr,SMS} \cdot U_{m,max}^4 \cdot f_1 + 432 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^3 \cdot f_1^2 - 348 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^6 \cdot f_1^2 + 1284 \cdot \\
&\tau_{tr,SMS}^3 \cdot U_{m,max}^3 \cdot f_1^2 + 72 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^2 \cdot f_1 - 312 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 \cdot f_1^2 - 48 \cdot \tau_{tr,SMS} \\
&\cdot U_{m,max}^3 \cdot f_1 + 252 \cdot U_{m,max}^3 \cdot f_1^2 - 84 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 \cdot f_1 - 6 \cdot \tau_{tr,SMS} \cdot U_{m,max}^5 \cdot f_1 - 12 \\
&\cdot \tau_{tr,SMS}^2 \cdot\cdot U_{m,max}^6 \cdot f_1 + 228 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^6 \cdot f_1 - 288 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^3 \cdot f_1 - 852 \cdot \\
&\tau_{tr,SMS}^3 \cdot U_{m,max}^5 \cdot f_1 - 288 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^5 \cdot f_1 + 432 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^4 \cdot f_1 + 72 \cdot \tau_{tr,SMS}^4 \\
&\cdot U_{m,max}^6 \cdot f_1 - 2322 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 \cdot f_1^4 - 180 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1^3 - 36 \cdot \tau_{tr,SMS}^3 \cdot \\
&U_{m,max}^6 \cdot f_1^3 - 1836 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1^3 - 1116 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^6 \cdot f_1^3 + 108 \cdot \tau_{tr,SMS}^3 \cdot \\
&U_{m,max}^4 \cdot f_1^3 + 36 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^5 \cdot f_1^3 + 2772 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 \cdot f_1^3 + 228 \cdot \tau_{tr,SMS} \cdot \\
&U_{m,max}^5 \cdot f_1^3 - 384 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 \cdot f_1^2 + 624 \cdot \tau_{tr,SMS} \cdot U_{m,max}^5 \cdot f_1^2 - 432 \cdot U_{m,max}^6 \cdot f_1^5 \\
&\cdot \tau_{tr,SMS} - 108 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^6 \cdot f_1^2 + 1458 \cdot U_{m,max}^5 \cdot f_1^5 \cdot \tau_{tr,SMS} - 396 \cdot U_{m,max}^3 \cdot f_1^4 \cdot \\
&\tau_{tr,SMS} + 924 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1^2 - 1566 \cdot U_{m,max}^4 \cdot f_1^5 \cdot \tau_{tr,SMS} + 294 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^6 \cdot \\
&f_1^2 - 180 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^3 \cdot f_1^3 + 1020 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 \cdot f_1^2 - 408 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 \cdot \\
&f_1^2 + 1356 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^5 \cdot f_1^2 - 1092 \cdot \tau_{tr,SMS} \cdot U_{m,max}^4 \cdot f_1^2 - 312 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 \cdot \\
&f_1^2 + 540 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 \cdot f_1^5 - 522 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1^2 + 432 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^5 \cdot f_1^2 \\
&+ 2025 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 \cdot f_1^4 - 108 \cdot U_{m,max}^2 \cdot f_1^4 \cdot \tau_{tr,SMS}^2 - 1020 \cdot U_{m,max}^3 \cdot f_1^3 \cdot \tau_{tr,SMS} - \\
&216 \cdot U_{m,max}^2 \cdot f_1^4 \cdot \tau_{tr,SMS} - 108 \cdot U_{m,max}^2 \cdot f_1^2 + 36 \cdot U_{m,max}^3 \cdot f_1^3 + 216 \cdot U_{m,max}^2 \cdot f_1^3 - \\
&12 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 + 36 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 + 108 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^3 - 24 \cdot \tau_{tr,SMS}^3 \cdot \\
&U_{m,max}^2 - 39 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^4 - 180 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^4 - 219 \cdot U_{m,max}^4 \cdot f_1^2 - 660 \cdot \\
&U_{m,max}^4 \cdot f_1^3 + 3246 \cdot U_{m,max}^4 \cdot f_1^4 - 1476 \cdot U_{m,max}^3 \cdot f_1^4 - 108 \cdot U_{m,max}^2 \cdot f_1^4 - 12 \cdot \tau_{tr,SMS}^4 \\
&\cdot U_{m,max}^2 + 48 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^3 - 72 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^4 + 84 \cdot U_{m,max}^5 \cdot f_1^2 + 576 \cdot \\
&U_{m,max}^5 \cdot f_1^3 - 2232 \cdot U_{m,max}^5 \cdot f_1^4 + 18 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^5 + 132 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^5 + 48 \cdot \\
&\tau_{tr,SMS}^4 \cdot U_{m,max}^5 - 36 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^6 - 3 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^6 - 12 \cdot \tau_{tr,SMS}^4 \cdot U_{m,max}^6 - \\
&144 \cdot U_{m,max}^6 \cdot f_1^3 + 504 \cdot U_{m,max}^6 \cdot f_1^4 - 12 \cdot U_{m,max}^6 \cdot f_1^2 - 528 \cdot U_{m,max}^6 \cdot f_1^5 + 2400 \cdot \\
&U_{m,max}^5 \cdot f_1^5 - 3636 \cdot U_{m,max}^4 \cdot f_1^5 + 180 \cdot U_{m,max}^6 \cdot f_1^6 - 828 \cdot U_{m,max}^5 \cdot f_1^6 + 1269 \cdot \\
&U_{m,max}^4 \cdot f_1^6 + 1836 \cdot U_{m,max}^3 \cdot f_1^5 - 648 \cdot U_{m,max}^3 \cdot f_1^6) - 12 \cdot U_{m,max} + 24 \cdot \tau_{tr,SMS} - 42 \cdot \\
&U_{m,max} \cdot f_1 + 51 \cdot U_{m,max}^2 \cdot f_1 -84 \cdot U_{m,max}^2 \cdot f_1^2 + 54 \cdot U_{m,max} \cdot f_1^2 - 66 \cdot \tau_{tr,SMS} \cdot U_{m,max} +
\end{aligned}$$

$57 \cdot \tau_{tr,SMS} \cdot U_{m,max}^2 - 17 \cdot U_{m,max}^3 \cdot\cdot f_1^3 + 27 \cdot U_{m,max}^2 \cdot f_1^3 + 6 \cdot U_{m,max}^2 - 78 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max} + 24 \cdot \tau_{tr,SMS}^2 - U_{m,max}^3 + 84 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^2 - 15 \cdot \tau_{tr,SMS} \cdot U_{m,max}^3 - 30 \cdot \tau_{tr,SMS}^2 \cdot U_{m,max}^3 - 8 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^3 + 24 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max}^2 - 24 \cdot \tau_{tr,SMS}^3 \cdot U_{m,max} + 8 \cdot \tau_{tr,SMS}^3)^{1/3}) - 1/3 \cdot \tau_{tr,SMS} \cdot U_{m,max} + 1/3 \cdot \tau_{tr,SMS} - 1/6 \cdot U_{m,max} + 1/6 \cdot U_{m,max} \cdot f_1 + 1/3$

12.2 Funnel Models for Double Workspace MTP

12.2.1 Function GenerateWorkpieceSpectrum

```
%Properties of Simulation

clear;

% Properties of Workpiece Spectrum

WSProbability=.5; % Value between 0 and 1 but not 0 or 1
NoWorkpieceTypes=5;

% Changeover of the workspace

DurationMeanChangeover= 1;
DurationVarChangeover= 0;

% Workspace #1 Part properties
NoStepsMean1 = 4;
NoStepsStD1 =0;
Technog1 = .75;
DurationMean1 = 1;
DurationVar1 =0;
LotSizeMean1=5;
LotSizeStD1=0;

% Workspace #2 Part properties ==> Differing Properties are to be activated
% below
NoStepsMean2 = 4;
NoStepsStD2 =0;
Technog2 = Technog1;
DurationMean2 = 1;
DurationVar2 =0;
LotSizeMean2=5;
LotSizeStD2=0;




% Generate TWPlist for workspace #1

WPlist1=GetWPlist(5,NoStepsMean1,NoStepsStD1,Technog1,DurationMean1,Duratio
nVar1);
TWPlist1=GetTWPlist(WPlist1);

% Generate TWPlist for workspace #2

%TWPlist2=TWPlist1;

%%{

% ACTIVATE DIFFERING PROPERTIES FOR WORKSPACE 2 HERE
```

```
WPlist2=GetWPlist(5,NoStepsMean2,NoStepsStD2,Technog2,DurationMean2,Duratio
nVar2);
TWPlist2=GetTWPlist(WPlist2);
%}
```

12.2.2 Function GetWPlist

```
function
[WPlist]=GetWPlist(NoWorkpieceTypes,NoStepsMean,NoStepsStD,Technog,Duration
Mean,DurationVar)

% Definition of the numbers of steps per workpiece type

for i=1:NoWorkpieceTypes;
    NoSteps(i)=0;
    while NoSteps(i)<=0
        NoSteps(i)=round(random('normal',NoStepsMean,NoStepsStD,1,1));
    end
end

% Definition of values in numbers of step in workpiece list

for i=1:NoWorkpieceTypes
    for j=1:NoSteps(i);
        WPlist(i,j,1)=j;


        % Assign Technology

        k=random('unif',0,1);
        if k>Technog
            WPlist(i,j,2)=2;
        else
            WPlist(i,j,2)=1;
        end

        % Assign Duration from Normal distribution
        WPlist(i,j,3)=0;
        while WPlist(i,j,3)<=0
            WPlist(i,j,3)=round(random('normal',DurationMean,DurationVar));
        end;
    end
end
```

12.2.3 Function GetTWPlist

```
function [TWPlist]= GetTWPlist(WPlist)

A=size(WPlist);
MaxNoSteps=A(1,2);

MaxNoWorkpieceTypes=A(1,1);


for l=1:MaxNoWorkpieceTypes;

    endMatrix=false;
    k=1;
```

```
    % Add the similar manuf. techn. together
    while endMatrix==false
        sequenceequal=true;
        Sum=WPlist(l,k,3);
        for j=k+1:MaxNoSteps
            if sequenceequal == true
                if WPlist(l,k,2)==WPlist(l,j,2)
                    Sum=Sum+WPlist(l,j,3);
                    if j == MaxNoSteps
                        sequenceequal = false;
                        SequenceStop = MaxNoSteps;
                    end
                else
                    sequenceequal=false;
                    SequenceStop=j;
                    if j == MaxNoSteps
                        TWPlist(l,j,3)=WPlist(l,j,3);
                        TWPlist(l,j,2)=WPlist(l,j,2);
                    end
                end;
            end;
        end
        TWPlist(l,k,3)=Sum;
        TWPlist(l,k,2)=WPlist(l,k,2);
        k=SequenceStop;
        if k==MaxNoSteps
            endMatrix=true;
        end
    end
end

% Eliminating Zeros

B=size(TWPlist);
MaxNoSteps=B(1,2);

for l=1:MaxNoWorkpieceTypes
    for h=1:MaxNoSteps
        for j = 1:MaxNoSteps
            if TWPlist(l,j,2)==0
                for k = j:MaxNoSteps-1
                    TWPlist(l,k,2)=TWPlist(l,k+1,2);
                    TWPlist(l,k+1,2)=0;
                    TWPlist(l,k,3)=TWPlist(l,k+1,3);
                    TWPlist(l,k+1,3)=0;
                end
            end
        end
    end
end

% Assigning the number for steps

for l = 1:MaxNoWorkpieceTypes
    for j=1:MaxNoSteps
        if TWPlist(l,j,2)~=0
            TWPlist(l,j,1)=j;
        end
    end
end;
```

12.2.4 Function Run

```
TimeCrit=1000;

% Definition muarrival: start- step- end
muarrival=[5 1 50];
NumberofRuns=(muarrival(3)-muarrival(1))/muarrival(2)

% Time of average order



i=1;
for mu=muarrival(1):muarrival(2):muarrival(3)
    i
    [Process-
cess-
ingWS1,ProcessingWS2,CompletedOrdersWS1,CompletedOrdersWS2,Orderlist]=Simul
ation(mu,TimeCrit,TWPlist1,TWPlist2,WSProbability,NoWorkpieceTypes,LotSizeM
ean1,LotSizeStD1,LotSizeMean2,LotSizeStD2,DurationMeanChangeover,DurationVa
rChangeover);

    [Out-
put,MeanThroughputTimeRatio,MeanPercentageWaitingbeforeWorkspace,MeanPercen
tageWaitinginWork-
space]=Analysis(ProcessingWS1,ProcessingWS2,CompletedOrdersWS1,CompletedOrd
ersWS2,TimeCrit);

    % Identification of Output rate
    OutputRate=Output/TimeCrit; % Reference is single workspace

    % Identification of Input rate
    SizeOrderlist=size(Orderlist);
    Input=0;
    for j=1:SizeOrderlist(1,1)
        if Orderlist(j,2)==1
            In-
put=Input+Orderlist(j,4)*sum(TWPlist1(Orderlist(j,3),:,3))+DurationMeanChan
geover;
        else
            In-
put=Input+Orderlist(j,4)*sum(TWPlist2(Orderlist(j,3),:,3))+DurationMeanChan
geover;
        end;
    end;
    InputRate=Input/TimeCrit;

    Result(i,1)=InputRate;
    Result(i,2)=OutputRate;
    Result(i,3)=MeanThroughputTimeRatio;
    Result(i,4)=MeanPercentageWaitingbeforeWorkspace;
    Result(i,5)=MeanPercentageWaitinginWorkspace;
    i=i+1;

end;
```

12.2.5 Function Analysis

```
function [Out-
put,MeanThroughputTimeRatio,MeanPercentageWaitingbeforeWorkspace,MeanPercen
```

```
tageWaitinginWork-
space]=Analysis(ProcessingWS1,ProcessingWS2,CompletedOrdersWS1,CompletedOrd
ersWS2,TimeCrit)

% Analysis of orders in workspace 1

NumberofCompletedOrdersWS1=length(CompletedOrdersWS1);

% The matrix CompletedOrders has the following structure: Ordernumber- time
% of arrival- time of entering the workspace- time of start machining time
% of completion- duration of machining- waiting in workspace- waiting
% before workspace- changeover time - operation time

for i=1:NumberofCompletedOrdersWS1

    % Identify time of arrival

    t=1;
    while ProcessingWS1(i,t)==0
        t=t+1;
    end;
    CompletedOrdersWS1(2,i)=t;


    % Identify time of start changeover

    while ProcessingWS1(i,t)==3
        t=t+1;
    end;
    CompletedOrdersWS1(3,i)=t;


    % Identify time of start operation

    while ProcessingWS1(i,t)==4
        t=t+1;
    end;
    CompletedOrdersWS1(4,i)=t;


    % Identify time of completed operation

    SizeProcessingWS1=size(ProcessingWS1);
    t=SizeProcessingWS1(1,2);

    while ProcessingWS1(i,t)==0
        t=t-1;
    end;
    CompletedOrdersWS1(5,i)=t;


    % Identify duration of machining and pauses
    CounterOP=0;
    CounterPause=0;
    for toperation=CompletedOrdersWS1(4,i):CompletedOrdersWS1(5,i)
        if ProcessingWS1(i,toperation) ~= 0
            CounterOP=CounterOP+1;
        else
            CounterPause=CounterPause+1;
        end;
```

```
    end;
    CompletedOrdersWS1(6,i)=CounterOP;
    CompletedOrdersWS1(7,i)=CounterPause;

    % Identify duration of waiting before entering the workspace

    CompletedOrdersWS1(8,i)=CompletedOrdersWS1(3,i)-
CompletedOrdersWS1(2,i);

    % Identification of changeover time and

    CompletedOrdersWS1(9,i)=CompletedOrdersWS1(4,i)-
CompletedOrdersWS1(3,i);

    % Identification of operation time

    Com-
pletedOrdersWS1(10,i)=CompletedOrdersWS1(6,i)+CompletedOrdersWS1(9,i);

end;


% Analysis of orders in workspace 2

NumberofCompletedOrdersWS2=length(CompletedOrdersWS2);

for i=1:NumberofCompletedOrdersWS2

    % Identify time of arrival

    t=1;
    while ProcessingWS2(i,t)==0
        t=t+1;
    end;
    CompletedOrdersWS2(2,i)=t;


    % Identify time of start changeover

    while ProcessingWS2(i,t)==3
        t=t+1;
    end;
    CompletedOrdersWS2(3,i)=t;


    % Identify time of start operation

    while ProcessingWS2(i,t)==4
        t=t+1;
    end;
    CompletedOrdersWS2(4,i)=t;


    % Identify time of completed operation

    SizeProcessingWS2=size(ProcessingWS2);
    t=SizeProcessingWS2(1,2);

    while ProcessingWS2(i,t)==0
```

```
        t=t-1;
    end;
    CompletedOrdersWS2(5,i)=t;


    % Identify duration of operation
    CounterOP=0;
    CounterPause=0;
    for toperation=CompletedOrdersWS2(4,i):CompletedOrdersWS2(5,i)
        if ProcessingWS2(i,toperation) ~= 0
            CounterOP=CounterOP+1;
        else
            CounterPause=CounterPause+1;
        end;
    end;
    CompletedOrdersWS2(6,i)=CounterOP;
    CompletedOrdersWS2(7,i)=CounterPause;


    % Identify duration of waiting before entering the workspace

    CompletedOrdersWS2(8,i)=CompletedOrdersWS2(3,i)-
CompletedOrdersWS2(2,i);

    % Identification of changeover time and

    CompletedOrdersWS2(9,i)=CompletedOrdersWS2(4,i)-
CompletedOrdersWS2(3,i);

    % Identification of operation time

    Com-
pletedOrdersWS2(10,i)=CompletedOrdersWS2(6,i)+CompletedOrdersWS2(9,i);
end;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%JOINT ANALYSIS OF BOTH WORKSPACES - IS ONLY FEASIBLE IF THE INPUT TO BOTH
%WORKSPACES HAS SIMILAR PROPERTIES


% Joining the two matrices

CompletedOrders=[CompletedOrdersWS1 CompletedOrdersWS2];


% Identification of output

CompletedOrders=sortrows(CompletedOrders',5);
SizeCompletedOrders=size(CompletedOrders);

Output=sum(CompletedOrders(:,10));


% Identification of input
% Input is the sum of Ouput plus those orders which were not completed
```

```
% Identification of throughput time

for i=1:SizeCompletedOrders(1,1)-1
    Throughput-
Time(i)=CompletedOrders(i,6)+CompletedOrders(i,7)+CompletedOrders(i,8);
    ThroughputTimeRatio(i)=ThroughputTime(i)/CompletedOrders(i,10);
    PercentageWaitingbeforeWork-
space(i)=CompletedOrders(i,8)/ThroughputTime(i);
    PercentageWaitinginWorkspace(i)=CompletedOrders(i,7)/ThroughputTime(i);
end;

MeanThroughputTimeRatio=mean(ThroughputTimeRatio);
MeanPercentageWaitingbeforeWork-
space=mean(PercentageWaitingbeforeWorkspace);
MeanPercentageWaitinginWorkspace=mean(PercentageWaitinginWorkspace);
```

12.2.6 Function Simulation for double workspace MTP config. 1

```
function [Process-
cess-
ingWS1,ProcessingWS2,CompletedOrdersWS1,CompletedOrdersWS2,Orderlist]=Simul
ation(muarrival,TimeCrit,TWPlist1,TWPlist2,WSProbability,NoWorkpieceTypes,L
otSize-
Mean1,LotSizeStD1,LotSizeMean2,LotSizeStD2,DurationMeanChangeover,DurationV
arChangeover)

Order-
list=GetOrderlist(TimeCrit,muarrival,WSProbability,NoWorkpieceTypes,LotSize
Mean1,LotSizeStD1,LotSizeMean2,LotSizeStD2);


ElementsinOrderlist=length(Orderlist);
Queue1=zeros(ElementsinOrderlist+1,1);
Queue2=zeros(ElementsinOrderlist+1,1);
Workspace1=zeros(TimeCrit,1);
Workspace2=zeros(TimeCrit,1);
Technology=zeros(TimeCrit,2);

ProcessDoneWS1=0;
ProcessDoneWS2=0;

TechnologyunavailableWS1=0;
TechnologyunavailableWS2=0;

OrderWS1=0;
OrderWS2=0;

CompletedOrdersWS1=0;
CompletedOrdersWS2=0;

for t=1:TimeCrit
    % Put Orders in Queue
    for k = 1:ElementsinOrderlist
        if Orderlist(k,1) == t
            if Orderlist(k,2) == 1
                lengthQueue1=0;
                while Queue1(lengthQueue1+1)~=0
                    lengthQueue1=lengthQueue1+1;
                end
```

```
                Queue1(lengthQueue1+1)=k;
            else
                lengthQueue2=0;
                while Queue2(lengthQueue2+1)~=0
                    lengthQueue2=lengthQueue2+1;
                end
                Queue2(lengthQueue2+1)=k;
            end
        end
    end


    % Check if Workspace 1 is free

    % Was a previous order processed?

   if Workspace1(t,1)==1
       % last workpiece in lot
       if CurrentWorkpieceWS1==Orderlist(OrderinProcessWS1,4)
           % are we processing the last process
           if CurrentProcessWS1==max(TWPlist1(CurrentWorkpieceTypeWS1,:,1))
               % Is the last process done?
               if t==ProcessDoneWS1
                   % Set Workspace free
                   for tremain=t:TimeCrit
                      Workspace1(tremain,1)=0;
                   end;

                   % Add OrderinProcess to List of completed orders for
                   % workspace 1
                   if CompletedOrdersWS1(1)==0
                       CompletedOrdersWS1(1)=OrderinProcessWS1;
                   else
                       lengthCompletedOrdersWS1=length(CompletedOrdersWS1);
                       Com-
pletedOrdersWS1(lengthCompletedOrdersWS1+1)=OrderinProcessWS1;
                   end;
               end;
           end;
       end;
   end;

    % Check if Workspace 2 is free

    % Was a previous order processed?

   if Workspace2(t,1)==1

       % last workpiece in lot
       if CurrentWorkpieceWS2==Orderlist(OrderinProcessWS2,4)
           % are we processing the last process
           if CurrentProcessWS2==max(TWPlist2(CurrentWorkpieceTypeWS2,:,1))
               % Is the last process done?
               if t==ProcessDoneWS2
                   % Set workspace 2 free
                   for tremain=t:TimeCrit
                      Workspace2(tremain,1)=0;
                   end;

                   % Add OrderinProcess to List of completed orders for
                   % workspace 2
                   if CompletedOrdersWS2(1)==0
```

```
                        CompletedOrdersWS2(1)=OrderinProcessWS2;
                    else
                        lengthCompletedOrdersWS2=length(CompletedOrdersWS2);
                        Com-
pletedOrdersWS2(lengthCompletedOrdersWS2+1)=OrderinProcessWS2;
                    end;
                end;
            end;
        end;
    end;




    % Check, if new order may enter the Workspace 1
    if Workspace1(t,1)==0
        if Queue1(1)~=0

            % Identify order
            OrderinProcessWS1=Queue1(1);
            % Identify workpiece type
            CurrentWorkpieceTypeWS1=Orderlist(OrderinProcessWS1,3);
            % Start with first workpiece
            CurrentWorkpieceWS1=1;
            % Start at first process
            CurrentProcessWS1=0;
            % Draw a random figure for the reconfiguration of the workspace
            DurationChangeoverWS1=0;
            while DurationChangeoverWS1<=0
                DurationChangeo-
verWS1=round(random('normal',DurationMeanChangeover,DurationVarChangeover))
;
            end;
            % Determine the time when the changeover of the workspace 1
            % will be over:
            ChangeoverDoneWS1=t+DurationChangeoverWS1;
            % Shift Queue up by 1
            for j=1:length(Queue1)-1
                Queue1(j)=Queue1(j+1);
            end
            % Block Workspace

            for remaint=t:TimeCrit
                Workspace1(remaint)=1;
            end

            % Graphical Output
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            OrderWS1=OrderWS1+1;

            % Mark duration of waiting
            if Orderlist(OrderinProcessWS1,1)<t-1
                for tgraph=Orderlist(OrderinProcessWS1,1):t-1
                    ProcessingWS1(OrderWS1,tgraph)=3; %Waiting
                end;
            end;

            % Mark duration of Changeover
            for tgraph=t:ChangeoverDoneWS1;
                ProcessingWS1(OrderWS1,tgraph)=4; %Setup
            end;

        end
```

```
    end

    % Check, if new order may enter the Workspace 2
    if Workspace2(t,1)==0;
        if Queue2(1)~=0
            % Identify order
            OrderinProcessWS2=Queue2(1);
            % Identify workpiece type
            CurrentWorkpieceTypeWS2=Orderlist(OrderinProcessWS2,3);
            % Start with first workpiece
            CurrentWorkpieceWS2=1;
            % Start at first process
            CurrentProcessWS2=0;
            % Draw a random figure for the reconfiguration of the workspace
            DurationChangeoverWS2=0;
            while DurationChangeoverWS2<=0
                DurationChangeo-
verWS2=round(random('normal',DurationMeanChangeover,DurationVarChangeover))
;
            end;
            % Determine the time when the changeover of the workspace 2
            % will be over:
            ChangeoverDoneWS2=t+DurationChangeoverWS2;

            for j=1:length(Queue2)-1
                Queue2(j)=Queue2(j+1);
            end
            % Block Workspace

            for remaint=t:TimeCrit
                Workspace2(remaint)=1;
            end

            % Graphical Output
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            OrderWS2=OrderWS2+1;

            % Mark duration of waiting
            if Orderlist(OrderinProcessWS2,1)<t-1
                for tgraph=Orderlist(OrderinProcessWS2,1):t-1
                    ProcessingWS2(OrderWS2,tgraph)=3; %Waiting
                end;
            end;

            % Mark duration of Changeover
            for tgraph=t:ChangeoverDoneWS2;
                ProcessingWS2(OrderWS2,tgraph)=4; %Setup
            end;
        end
    end


   %}

    % Check, if workpiece in workspace 1 may be processed
    % There must be a workpiece in workspace 1

    if Workspace1(t,1)==1
        % Check if the changeover of the workspace has been completed

        if t>=ChangeoverDoneWS1
```

```
            % Check if the previous process has been completed

            if t >=ProcessDoneWS1

                % The next process may only be started if the
                % technology was available for the last t

                if TechnologyunavailableWS1==0

                % Check if a workpiece has been completed
                % Identify the number of processes for CurrentWork-
pieceType1


                    NumberofProcess-
esWS1=max(TWPlist1(CurrentWorkpieceTypeWS1,:,1));
                    if CurrentProcessWS1+1<=NumberofProcessesWS1
                        CurrentProcessWS1=CurrentProcessWS1+1;
                    else
                        CurrentWorkpieceWS1=CurrentWorkpieceWS1+1;
                        CurrentProcessWS1=1;
                    end;
                end;



                % Which technology is required?
                RequiredTechnolo-
gyWS1=TWPlist1(CurrentWorkpieceTypeWS1,CurrentProcessWS1,2);

                % Is Technology available

                if Technology(t,RequiredTechnologyWS1)==0
                    % Duration of Process
                    DurationofPro-
cessWS1=TWPlist1(CurrentWorkpieceTypeWS1,CurrentProcessWS1,3);

                    % Block Technology for the duration of the process
                    for tdurationWS1=0:DurationofProcessWS1-1
                        Technology(t+tdurationWS1,RequiredTechnologyWS1)=1;
                        Pro-
cessingWS1(OrderWS1,t+tdurationWS1)=RequiredTechnologyWS1;
                    end;
                    ProcessDoneWS1=t+DurationofProcessWS1;
                    TechnologyunavailableWS1=0;




                else
                    TechnologyunavailableWS1=1;
                end;

            end;
        end;
    end;



    % Check, if workpiece in workspace 2 may be processed
    % There must be a workpiece in workspace 2
```

```
    if Workspace2(t,1)==1
        % Check if the changeover of the workspace has been completed

        if t>=ChangeoverDoneWS2

            % Check if the previous process has been completed

            if t >=ProcessDoneWS2

                % The next process may only be started if the last
                % technology was available

                if TechnologyunavailableWS2==0

                    % Check if a workpiece has been completed
                    % Identify the number of processes for CurrentWork-
pieceType1

                    NumberofProcess-
esWS2=max(TWPlist2(CurrentWorkpieceTypeWS2,:,1));
                    if CurrentProcessWS2+1<=NumberofProcessesWS2
                        CurrentProcessWS2=CurrentProcessWS2+1;
                    else
                        CurrentWorkpieceWS2=CurrentWorkpieceWS2+1;
                        CurrentProcessWS2=1;
                    end;
                end;



                % Which technology is required?
                RequiredTechnolo-
gyWS2=TWPlist2(CurrentWorkpieceTypeWS2,CurrentProcessWS2,2);

                % Is Technology available
                if Technology(t,RequiredTechnologyWS2)==0
                    % Duration of Process
                    DurationofPro-
cessWS2=TWPlist2(CurrentWorkpieceTypeWS2,CurrentProcessWS2,3);

                    % Block Technology for the duration of the process
                    for tdurationWS2=0:DurationofProcessWS2-1
                        Technology(t+tdurationWS2,RequiredTechnologyWS2)=1;
                        Pro-
cessingWS2(OrderWS2,t+tdurationWS2)=RequiredTechnologyWS2;
                    end;
                    ProcessDoneWS2=t+DurationofProcessWS2;
                    TechnologyunavailableWS2=0;
                else
                    TechnologyunavailableWS2=1;
                end;
            end;
        end;
    end;
end

% WS1: Add those orders to the ProcessingWS1 which are still in the queue
at the
% end of TimeCrit

i=1;
while Queue1(i)~=0
```

```
    OrderNumber=Queue1(i);
    TimeofAppearance=Orderlist(OrderNumber,1);
    CurrentSizeProcessingWS1=size(ProcessingWS1);
    for tfillup=TimeofAppearance:TimeCrit
        ProcessingWS1(CurrentSizeProcessingWS1(1,1)+1,tfillup)=3;
    end;
    i=i+1;
end;


% WS2: Add those orders to the ProcessingWS2 which are still in the queue
at the
% end of TimeCrit

i=1;
while Queue2(i)~=0
    OrderNumber=Queue2(i);
    TimeofAppearance=Orderlist(OrderNumber,1);
    CurrentSizeProcessingWS2=size(ProcessingWS2);
    for tfillup=TimeofAppearance:TimeCrit
        ProcessingWS2(CurrentSizeProcessingWS2(1,1)+1,tfillup)=3;
    end;
    i=i+1;
end;
```

12.2.7 Function Simulation for double workspace MTP config. 2

```
function [Process-
cess-
ingWS1,ProcessingWS2,CompletedOrdersWS1,CompletedOrdersWS2,Orderlist]=Simul
ation(muarrival,TimeCrit,TWPlist1,TWPlist2,WSProbability,NoWorkpieceTypes,L
otSize-
Mean1,LotSizeStD1,LotSizeMean2,LotSizeStD2,DurationMeanChangeover,DurationV
arChangeover)

Order-
list=GetOrderlist(TimeCrit,muarrival,WSProbability,NoWorkpieceTypes,LotSize
Mean1,LotSizeStD1,LotSizeMean2,LotSizeStD2);



ElementsinOrderlist=length(Orderlist);
Queue1=zeros(ElementsinOrderlist+1,1);
Queue2=zeros(ElementsinOrderlist+1,1);
Workspace1=zeros(TimeCrit,1);
Workspace2=zeros(TimeCrit,1);
Technology=zeros(TimeCrit,2);

ProcessDoneWS1=0;
ProcessDoneWS2=0;

TechnologyunavailableWS1=0;
TechnologyunavailableWS2=0;

OrderWS1=0;
OrderWS2=0;

CompletedOrdersWS1=0;
CompletedOrdersWS2=0;

for t=1:TimeCrit
    % Put Orders in Queue
```

```
    for k = 1:ElementsinOrderlist
        if Orderlist(k,1) == t
            if Orderlist(k,2) == 1
                lengthQueue1=0;
                while Queue1(lengthQueue1+1)~=0
                    lengthQueue1=lengthQueue1+1;
                end
                Queue1(lengthQueue1+1)=k;
            else
                lengthQueue2=0;
                while Queue2(lengthQueue2+1)~=0
                    lengthQueue2=lengthQueue2+1;
                end
                Queue2(lengthQueue2+1)=k;
            end
        end
    end


    % Check if Workspace 1 is free

    % Was a previous order processed?

   if Workspace1(t,1)==1
       % last workpiece in lot
       if CurrentWorkpieceWS1==Orderlist(OrderinProcessWS1,4)
           % are we processing the last process
           if CurrentProcessWS1==max(TWPlist1(CurrentWorkpieceTypeWS1,:,1))
               % Is the last process done?
               if t==ProcessDoneWS1
                   % Set Workspace free
                   for tremain=t:TimeCrit
                      Workspace1(tremain,1)=0;
                   end;

                   % Add OrderinProcess to List of completed orders for
                   % workspace 1
                   if CompletedOrdersWS1(1)==0
                       CompletedOrdersWS1(1)=OrderinProcessWS1;
                   else
                       lengthCompletedOrdersWS1=length(CompletedOrdersWS1);
                       Com-
pletedOrdersWS1(lengthCompletedOrdersWS1+1)=OrderinProcessWS1;
                   end;
               end;
           end;
       end;
   end;

    % Check if Workspace 2 is free

    % Was a previous order processed?

   if Workspace2(t,1)==1

       % last workpiece in lot
       if CurrentWorkpieceWS2==Orderlist(OrderinProcessWS2,4)
           % are we processing the last process
           if CurrentProcessWS2==max(TWPlist2(CurrentWorkpieceTypeWS2,:,1))
               % Is the last process done?
               if t==ProcessDoneWS2
                   % Set workspace 2 free
```

```
                   for tremain=t:TimeCrit
                      Workspace2(tremain,1)=0;
                   end;

                   % Add OrderinProcess to List of completed orders for
                   % workspace 2
                   if CompletedOrdersWS2(1)==0
                       CompletedOrdersWS2(1)=OrderinProcessWS2;
                   else
                       lengthCompletedOrdersWS2=length(CompletedOrdersWS2);
                       Com-
pletedOrdersWS2(lengthCompletedOrdersWS2+1)=OrderinProcessWS2;
                   end;
               end;
           end;
       end;
   end;




    % Check, if new order may enter the Workspace 1
    if Workspace1(t,1)==0
        if Queue1(1)~=0

            % Identify order
            OrderinProcessWS1=Queue1(1);
            % Identify workpiece type
            CurrentWorkpieceTypeWS1=Orderlist(OrderinProcessWS1,3);
            % Start with first workpiece
            CurrentWorkpieceWS1=1;
            % Start at first process
            CurrentProcessWS1=0;
            % Draw a random figure for the reconfiguration of the workspace
            DurationChangeoverWS1=0;
            while DurationChangeoverWS1<=0
                DurationChangeo-
verWS1=round(random('normal',DurationMeanChangeover,DurationVarChangeover))
;
            end;
            % Determine the time when the changeover of the workspace 1
            % will be over:
            ChangeoverDoneWS1=t+DurationChangeoverWS1;
            % Shift Queue up by 1
            for j=1:length(Queue1)-1
                Queue1(j)=Queue1(j+1);
            end
            % Block Workspace

            for remaint=t:TimeCrit
                Workspace1(remaint)=1;
            end

            % Graphical Output
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            OrderWS1=OrderWS1+1;

            % Mark duration of waiting
            if Orderlist(OrderinProcessWS1,1)<t-1
                for tgraph=Orderlist(OrderinProcessWS1,1):t-1
                    ProcessingWS1(OrderWS1,tgraph)=3; %Waiting
                end;
            end;
```

```
            % Mark duration of Changeover
            for tgraph=t:ChangeoverDoneWS1;
                ProcessingWS1(OrderWS1,tgraph)=4; %Setup
            end;

        end
    end

    % Check, if new order may enter the Workspace 2
    if Workspace2(t,1)==0;
        if Queue2(1)~=0
            % Identify order
            OrderinProcessWS2=Queue2(1);
            % Identify workpiece type
            CurrentWorkpieceTypeWS2=Orderlist(OrderinProcessWS2,3);
            % Start with first workpiece
            CurrentWorkpieceWS2=1;
            % Start at first process
            CurrentProcessWS2=0;
            % Draw a random figure for the reconfiguration of the workspace
            DurationChangeoverWS2=0;
            while DurationChangeoverWS2<=0
                DurationChangeo-
verWS2=round(random('normal',DurationMeanChangeover,DurationVarChangeover))
;
            end;
            % Determine the time when the changeover of the workspace 2
            % will be over:
            ChangeoverDoneWS2=t+DurationChangeoverWS2;

            for j=1:length(Queue2)-1
                Queue2(j)=Queue2(j+1);
            end
            % Block Workspace

            for remaint=t:TimeCrit
                Workspace2(remaint)=1;
            end

            % Graphical Output
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            OrderWS2=OrderWS2+1;

            % Mark duration of waiting
            if Orderlist(OrderinProcessWS2,1)<t-1
                for tgraph=Orderlist(OrderinProcessWS2,1):t-1
                    ProcessingWS2(OrderWS2,tgraph)=3; %Waiting
                end;
            end;

            % Mark duration of Changeover
            for tgraph=t:ChangeoverDoneWS2;
                ProcessingWS2(OrderWS2,tgraph)=4; %Setup
            end;
        end
    end


   %}

    % Check, if workpiece in workspace 1 may be processed
```

```
    % There must be a workpiece in workspace 1

    if Workspace1(t,1)==1
        % Check if the changeover of the workspace has been completed

        if t>=ChangeoverDoneWS1

            % Check if the previous process has been completed

            if t >=ProcessDoneWS1

                % The next process may only be started if the
                % technology was available for the last t

                if TechnologyunavailableWS1==0

                % Check if a workpiece has been completed
                % Identify the number of processes for CurrentWork-
pieceType1


                    NumberofProcess-
esWS1=max(TWPlist1(CurrentWorkpieceTypeWS1,:,1));
                    if CurrentProcessWS1+1<=NumberofProcessesWS1
                        CurrentProcessWS1=CurrentProcessWS1+1;
                    else
                        CurrentWorkpieceWS1=CurrentWorkpieceWS1+1;
                        CurrentProcessWS1=1;
                    end;
                end;



                % Which technology is required?
                RequiredTechnolo-
gyWS1=TWPlist1(CurrentWorkpieceTypeWS1,CurrentProcessWS1,2);

                % Is Technology available

                if Technology(t,RequiredTechnologyWS1)==0
                    % Duration of Process
                    DurationofPro-
cessWS1=TWPlist1(CurrentWorkpieceTypeWS1,CurrentProcessWS1,3);

                    % Block Technology for the duration of the process
                    for tdurationWS1=0:DurationofProcessWS1-1
                        if RequiredTechnologyWS1==2;
                            Technolo-
gy(t+tdurationWS1,RequiredTechnologyWS1)=1;
                        end;
                        Pro-
cessingWS1(OrderWS1,t+tdurationWS1)=RequiredTechnologyWS1;
                    end;
                    ProcessDoneWS1=t+DurationofProcessWS1;
                    TechnologyunavailableWS1=0;




                else
                    TechnologyunavailableWS1=1;
                end;
```

```
            end;
        end;
    end;


    % Check, if workpiece in workspace 2 may be processed
    % There must be a workpiece in workspace 2

    if Workspace2(t,1)==1
        % Check if the changeover of the workspace has been completed

        if t>=ChangeoverDoneWS2

            % Check if the previous process has been completed

            if t >=ProcessDoneWS2

                % The next process may only be started if the last
                % technology was available

                if TechnologyunavailableWS2==0

                    % Check if a workpiece has been completed
                    % Identify the number of processes for CurrentWork-
pieceType1

                    NumberofProcess-
esWS2=max(TWPlist2(CurrentWorkpieceTypeWS2,:,1));
                    if CurrentProcessWS2+1<=NumberofProcessesWS2
                        CurrentProcessWS2=CurrentProcessWS2+1;
                    else
                        CurrentWorkpieceWS2=CurrentWorkpieceWS2+1;
                        CurrentProcessWS2=1;
                    end;
                end;



                % Which technology is required?
                RequiredTechnolo-
gyWS2=TWPlist2(CurrentWorkpieceTypeWS2,CurrentProcessWS2,2);

                % Is Technology available
                if Technology(t,RequiredTechnologyWS2)==0
                    % Duration of Process
                    DurationofPro-
cessWS2=TWPlist2(CurrentWorkpieceTypeWS2,CurrentProcessWS2,3);

                    % Block Technology for the duration of the process
                    for tdurationWS2=0:DurationofProcessWS2-1
                        if RequiredTechnologyWS2==2;
                            Technolo-
gy(t+tdurationWS2,RequiredTechnologyWS2)=1;
                        end;
                        Pro-
cessingWS2(OrderWS2,t+tdurationWS2)=RequiredTechnologyWS2;
                    end;
                    ProcessDoneWS2=t+DurationofProcessWS2;
                    TechnologyunavailableWS2=0;
                else
                    TechnologyunavailableWS2=1;
```

```
                end;
            end;
        end;
    end;
end

% WS1: Add those orders to the ProcessingWS1 which are still in the queue
at the
% end of TimeCrit

i=1;
while Queue1(i)~=0
    OrderNumber=Queue1(i);
    TimeofAppearance=Orderlist(OrderNumber,1);
    CurrentSizeProcessingWS1=size(ProcessingWS1);
    for tfillup=TimeofAppearance:TimeCrit
        ProcessingWS1(CurrentSizeProcessingWS1(1,1)+1,tfillup)=3;
    end;
    i=i+1;
end;



% WS2: Add those orders to the ProcessingWS2 which are still in the queue
at the
% end of TimeCrit

i=1;
while Queue2(i)~=0
    OrderNumber=Queue2(i);
    TimeofAppearance=Orderlist(OrderNumber,1);
    CurrentSizeProcessingWS2=size(ProcessingWS2);
    for tfillup=TimeofAppearance:TimeCrit
        ProcessingWS2(CurrentSizeProcessingWS2(1,1)+1,tfillup)=3;
    end;
    i=i+1;
end;
```

12.2.8 Function Simulation for single workspace MTP (Reference)

```
function [Process-
cess-
ingWS1,ProcessingWS2,CompletedOrdersWS1,CompletedOrdersWS2,Orderlist]=Simul
ation(muarrival,TimeCrit,TWPlist1,TWPlist2,WSProbability,NoWorkpieceTypes,L
otSize-
Mean1,LotSizeStD1,LotSizeMean2,LotSizeStD2,DurationMeanChangeover,DurationV
arChangeover)

Order-
list=GetOrderlist(TimeCrit,muarrival,WSProbability,NoWorkpieceTypes,LotSize
Mean1,LotSizeStD1,LotSizeMean2,LotSizeStD2);



ElementsinOrderlist=length(Orderlist);
Queue1=zeros(ElementsinOrderlist+1,1);
Queue2=zeros(ElementsinOrderlist+1,1);
Workspace1=zeros(TimeCrit,1);
Workspace2=zeros(TimeCrit,1);
Technology=zeros(TimeCrit,2);

ProcessDoneWS1=0;
ProcessDoneWS2=0;
```

```
TechnologyunavailableWS1=0;
TechnologyunavailableWS2=0;

OrderWS1=0;
OrderWS2=0;

CompletedOrdersWS1=0;
CompletedOrdersWS2=0;

for t=1:TimeCrit
    % Put Orders in Queue
    for k = 1:ElementsinOrderlist
        if Orderlist(k,1) == t
            if Orderlist(k,2) == 1
                lengthQueue1=0;
                while Queue1(lengthQueue1+1)~=0
                    lengthQueue1=lengthQueue1+1;
                end
                Queue1(lengthQueue1+1)=k;
            else
                lengthQueue2=0;
                while Queue2(lengthQueue2+1)~=0
                    lengthQueue2=lengthQueue2+1;
                end
                Queue2(lengthQueue2+1)=k;
            end
        end
    end


    % Check if Workspace 1 is free

    % Was a previous order processed?

   if Workspace1(t,1)==1
       % last workpiece in lot
       if CurrentWorkpieceWS1==Orderlist(OrderinProcessWS1,4)
           % are we processing the last process
           if CurrentProcessWS1==max(TWPlist1(CurrentWorkpieceTypeWS1,:,1))
               % Is the last process done?
               if t==ProcessDoneWS1
                   % Set Workspace free
                   for tremain=t:TimeCrit
                      Workspace1(tremain,1)=0;
                   end;

                   % Add OrderinProcess to List of completed orders for
                   % workspace 1
                   if CompletedOrdersWS1(1)==0
                       CompletedOrdersWS1(1)=OrderinProcessWS1;
                   else
                       lengthCompletedOrdersWS1=length(CompletedOrdersWS1);
                       Com-
pletedOrdersWS1(lengthCompletedOrdersWS1+1)=OrderinProcessWS1;
                   end;
               end;
           end;
       end;
   end;

    % Check if Workspace 2 is free
```

```
    % Was a previous order processed?

   if Workspace2(t,1)==1

       % last workpiece in lot
       if CurrentWorkpieceWS2==Orderlist(OrderinProcessWS2,4)
           % are we processing the last process
           if CurrentProcessWS2==max(TWPlist2(CurrentWorkpieceTypeWS2,:,1))
               % Is the last process done?
               if t==ProcessDoneWS2
                   % Set workspace 2 free
                   for tremain=t:TimeCrit
                      Workspace2(tremain,1)=0;
                   end;

                   % Add OrderinProcess to List of completed orders for
                   % workspace 2
                   if CompletedOrdersWS2(1)==0
                       CompletedOrdersWS2(1)=OrderinProcessWS2;
                   else
                       lengthCompletedOrdersWS2=length(CompletedOrdersWS2);
                       Com-
pletedOrdersWS2(lengthCompletedOrdersWS2+1)=OrderinProcessWS2;
                   end;
               end;
           end;
       end;
   end;




    % Check, if new order may enter the Workspace 1
    if Workspace1(t,1)==0
        if Queue1(1)~=0

            % Identify order
            OrderinProcessWS1=Queue1(1);
            % Identify workpiece type
            CurrentWorkpieceTypeWS1=Orderlist(OrderinProcessWS1,3);
            % Start with first workpiece
            CurrentWorkpieceWS1=1;
            % Start at first process
            CurrentProcessWS1=0;
            % Draw a random figure for the reconfiguration of the workspace
            DurationChangeoverWS1=0;
            while DurationChangeoverWS1<=0
                DurationChangeo-
verWS1=round(random('normal',DurationMeanChangeover,DurationVarChangeover))
;
            end;
            % Determine the time when the changeover of the workspace 1
            % will be over:
            ChangeoverDoneWS1=t+DurationChangeoverWS1;
            % Shift Queue up by 1
            for j=1:length(Queue1)-1
                Queue1(j)=Queue1(j+1);
            end
            % Block Workspace

            for remaint=t:TimeCrit
                Workspace1(remaint)=1;
```

```
            end

            % Graphical Output
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            OrderWS1=OrderWS1+1;

            % Mark duration of waiting
            if Orderlist(OrderinProcessWS1,1)<t-1
                for tgraph=Orderlist(OrderinProcessWS1,1):t-1
                    ProcessingWS1(OrderWS1,tgraph)=3; %Waiting
                end;
            end;

            % Mark duration of Changeover
            for tgraph=t:ChangeoverDoneWS1;
                ProcessingWS1(OrderWS1,tgraph)=4; %Setup
            end;

        end
    end

    % Check, if new order may enter the Workspace 2
    if Workspace2(t,1)==0;
        if Queue2(1)~=0
            % Identify order
            OrderinProcessWS2=Queue2(1);
            % Identify workpiece type
            CurrentWorkpieceTypeWS2=Orderlist(OrderinProcessWS2,3);
            % Start with first workpiece
            CurrentWorkpieceWS2=1;
            % Start at first process
            CurrentProcessWS2=0;
            % Draw a random figure for the reconfiguration of the workspace
            DurationChangeoverWS2=0;
            while DurationChangeoverWS2<=0
                DurationChangeo-
verWS2=round(random('normal',DurationMeanChangeover,DurationVarChangeover))
;
            end;
            % Determine the time when the changeover of the workspace 2
            % will be over:
            ChangeoverDoneWS2=t+DurationChangeoverWS2;

            for j=1:length(Queue2)-1
                Queue2(j)=Queue2(j+1);
            end
            % Block Workspace

            for remaint=t:TimeCrit
                Workspace2(remaint)=1;
            end

            % Graphical Output
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            OrderWS2=OrderWS2+1;

            % Mark duration of waiting
            if Orderlist(OrderinProcessWS2,1)<t-1
                for tgraph=Orderlist(OrderinProcessWS2,1):t-1
                    ProcessingWS2(OrderWS2,tgraph)=3; %Waiting
                end;
            end;
```

```
            % Mark duration of Changeover
            for tgraph=t:ChangeoverDoneWS2;
                ProcessingWS2(OrderWS2,tgraph)=4; %Setup
            end;
        end
    end


   %}

    % Check, if workpiece in workspace 1 may be processed
    % There must be a workpiece in workspace 1

    if Workspace1(t,1)==1
        % Check if the changeover of the workspace has been completed

        if t>=ChangeoverDoneWS1

            % Check if the previous process has been completed

            if t >=ProcessDoneWS1

                % The next process may only be started if the
                % technology was available for the last t

                if TechnologyunavailableWS1==0

                % Check if a workpiece has been completed
                % Identify the number of processes for CurrentWork-
pieceType1


                    NumberofProcess-
esWS1=max(TWPlist1(CurrentWorkpieceTypeWS1,:,1));
                    if CurrentProcessWS1+1<=NumberofProcessesWS1
                        CurrentProcessWS1=CurrentProcessWS1+1;
                    else
                        CurrentWorkpieceWS1=CurrentWorkpieceWS1+1;
                        CurrentProcessWS1=1;
                    end;
                end;



                % Which technology is required?
                RequiredTechnolo-
gyWS1=TWPlist1(CurrentWorkpieceTypeWS1,CurrentProcessWS1,2);

                % Is Technology available

                if Technology(t,RequiredTechnologyWS1)==0
                    % Duration of Process
                    DurationofPro-
cessWS1=TWPlist1(CurrentWorkpieceTypeWS1,CurrentProcessWS1,3);

                    % Block Technology for the duration of the process
                    for tdurationWS1=0:DurationofProcessWS1-1
                        Technology(t+tdurationWS1,RequiredTechnologyWS1)=1;
                        Pro-
cessingWS1(OrderWS1,t+tdurationWS1)=RequiredTechnologyWS1;
```

```
                    end;
                    ProcessDoneWS1=t+DurationofProcessWS1;
                    TechnologyunavailableWS1=0;




                else
                    TechnologyunavailableWS1=1;
                end;

            end;
        end;
    end;


    % Check, if workpiece in workspace 2 may be processed
    % There must be a workpiece in workspace 2

    if Workspace2(t,1)==1
        % Check if the changeover of the workspace has been completed

        if t>=ChangeoverDoneWS2

            % Check if the previous process has been completed

            if t >=ProcessDoneWS2

                % The next process may only be started if the last
                % technology was available

                if TechnologyunavailableWS2==0

                    % Check if a workpiece has been completed
                    % Identify the number of processes for CurrentWork-
pieceType1

                    NumberofProcess-
esWS2=max(TWPlist2(CurrentWorkpieceTypeWS2,:,1));
                    if CurrentProcessWS2+1<=NumberofProcessesWS2
                        CurrentProcessWS2=CurrentProcessWS2+1;
                    else
                        CurrentWorkpieceWS2=CurrentWorkpieceWS2+1;
                        CurrentProcessWS2=1;
                    end;
                end;



                % Which technology is required?
                RequiredTechnolo-
gyWS2=TWPlist2(CurrentWorkpieceTypeWS2,CurrentProcessWS2,2);

                % Is Technology available
                if Technology(t,RequiredTechnologyWS2)==0
                    % Duration of Process
                    DurationofPro-
cessWS2=TWPlist2(CurrentWorkpieceTypeWS2,CurrentProcessWS2,3);

                    % Block Technology for the duration of the process
                    for tdurationWS2=0:DurationofProcessWS2-1
                        Technology(t+tdurationWS2,RequiredTechnologyWS2)=1;
```

```
                        Pro-
cessingWS2(OrderWS2,t+tdurationWS2)=RequiredTechnologyWS2;
                    end;
                    ProcessDoneWS2=t+DurationofProcessWS2;
                    TechnologyunavailableWS2=0;
                else
                    TechnologyunavailableWS2=1;
                end;
            end;
        end;
    end;
end

% WS1: Add those orders to the ProcessingWS1 which are still in the queue
at the
% end of TimeCrit

i=1;
while Queue1(i)~=0
    OrderNumber=Queue1(i);
    TimeofAppearance=Orderlist(OrderNumber,1);
    CurrentSizeProcessingWS1=size(ProcessingWS1);
    for tfillup=TimeofAppearance:TimeCrit
        ProcessingWS1(CurrentSizeProcessingWS1(1,1)+1,tfillup)=3;
    end;
    i=i+1;
end;


% WS2: Add those orders to the ProcessingWS2 which are still in the queue
at the
% end of TimeCrit

i=1;
while Queue2(i)~=0
    OrderNumber=Queue2(i);
    TimeofAppearance=Orderlist(OrderNumber,1);
    CurrentSizeProcessingWS2=size(ProcessingWS2);
    for tfillup=TimeofAppearance:TimeCrit
        ProcessingWS2(CurrentSizeProcessingWS2(1,1)+1,tfillup)=3;
    end;
    i=i+1;
end;
```

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Manufacturing technology integration is an arising paradigm that aims at the functional integration of diverse manufacturing technologies into machine tools which are called multi-technology platforms. So far, machine tool builders have attempted to justify manufacturing technology integration through the machine hour rate calculation. However, this calculation approach is inadequate for such purpose since it neglects output quantities and the configuration of the manufacturing system.

This dissertation applies models of production, cost, and queuing theory to derive the conditions under which manufacturing technology integration leads to greater productivity, lower cost, and smaller throughput times than a conventional manufacturing system consisting of single-technology machine tools. Such a conventional manufacturing system is called segregated manufacturing system. Based on the efficiency models the design of multi-technology platforms is discussed with regard to the number and the type of manufacturing technologies to be integrated as well as the number of workspaces. It is found that manufacturing technology integration is particularly cost-efficient for low output quantities.

However, although the logistic chain in a plant is shortened through manufacturing technology integration the throughput times of an integrated manufacturing system might be greater than the throughput times of a segregated manufacturing system. This is due to the fact that for low output quantities the resource utilization and as such the waiting times might be greater in an integrated manufacturing system than in a segregated manufacturing system.

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