

CHAPTER 15

ALTERNATIVE APPROACHES TO METALWORKING PROCESS ANALYSIS

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This chapter is based on a discussion of the Markowitz-Rowe study of metalworking as presented to the Cowles Foundation Seminar on Process Analysis, extended by a review of the Soviet Machinery Industry Study of the University of North Carolina (1959). The purpose of the paper is to compare these two alternative approaches to metalworking process analysis and to suggest ways of integrating them. Limitations of space have prevented including a review of several other relevant studies and the presentation of a technique for the formulation of development plans for the metalworking sector in underdeveloped countries. A more complete version of the paper is available as an IBM Research Report (Vietorisz, 1962).

The contribution of Markowitz and Rowe is an original, pioneering approach to the study of the metalworking sector. It offers a coherent set of principles for applying process analysis, at different levels of aggregation and with different degrees of complexity, to this sector which raises inherently more difficult problems of technological description than agriculture or the industries characterized primarily by chemical-type processes. The mechanical transformations dominant in metalworking involve the generation of three-dimensional geometric structures with prescribed properties of strength, hardness, and elasticity, which have to be evolved detail by precise detail, whereas the production processes of many other industries may rely on the simpler technique of controlling a limited number of key environmental or operating variables. Correspondingly, metalworking products show an almost endless variety, whereas the products of most other industries are relatively homogeneous. The technological description offered by Markowitz and Rowe cuts across this tremendous range of variation in a way which is not only applicable to the metalworking industries themselves, but also offers a guideline for work in other industries where mechanical transformations play an important role.

The central ideas of the Markowitz-Rowe approach may be summarized as:

1. The combined use of engineering and census data in requirements analysis, with a means of reconciling contradictions between them.

2. The description of technology in substitution analysis by means of the concepts of *standard tasks*, *standard machine classes*, the breakdown of a *time fund*, and *machine availability*.

3. The handling of demand in substitution analysis by a questionnaire survey of machine availabilities and task proportions or by the sampling of production paper.

4. The application of simulation techniques to the estimation of machine availabilities, to queueing, and to flexibility problems.

In the nature of a pioneering effort, the Markowitz-Rowe contribution is a mosaic of empirical work and methodological ideas. While the requirements analysis is formulated to cover the entire U. S. metalworking sector, substitution analysis is illustrated only by the case of machining and, at that, without an empirical demand estimate. The question arises: To what extent can the methodology of substitution between metalworking machine tools be extended to other metalworking operations? Furthermore, it is evident that the type of substitution between machines which is discussed by Markowitz and Rowe is only one of several kinds which may occur: others are substitution possibilities in product design or in materials; there are even substitution possibilities involving extrasectoral repercussions (e.g., numerous standard steel shapes combined with little machining, versus fewer standard steel shapes combined with more extensive machining). Finally, simulation is advanced only as a methodological suggestion, with no illustrative examples.

Another major independent investigation of the metalworking sector has been undertaken by the Institute for Research in Social Science of the University of North Carolina (1959). This is a study of Soviet machinery construction which contains an important methodological concept ("resource elements") and much useful empirical information. Both the above concept and the empirical data contained in this study are suitable for complementing the Markowitz-Rowe approach.

The Soviet Machinery Industry study was intended as a tool for estimating the economic capabilities of the Soviet Union. It was based on published Soviet engineering and industrial source material.

Technological coefficients were estimated in two stages. In the first stage, flow and capital coefficients were derived for basic metalworking operations including casting, forging, machining, stamping, upsetting, heat treatment, assembly, and welding. The coefficients were expressed as the physical quantities of inputs needed per unit of semifabricate output. In the second stage, typical end products (machines) were analyzed and estimates were made of the inputs of these semifabricates required per unit of machine output. The combination of these two types of coefficients subsequently yielded the estimates of flow and capital inputs required per unit of machine.

The level of aggregation chosen for the basic metalworking operations, in the final version of the study, corresponded approximately to the production shop or department. *Resource elements* or typical shops consist of coherent composites of capital equipment and floorspace, defined in such a way that a

variety of end products might draw upon the same resource element. This approach served several purposes. First, it was a means of representing the large variety of equipment combinations used for machinery production by a number of typical combinations. Second, while information on the relationship of particular inputs to end products was often unavailable, the resource elements provided a means of estimating the corresponding ratios. Third, resource elements provided a simple way of taking into account the fact that given productive facilities can be converted from one end product to another, for example, that a given forge can produce semifabricates for many different kinds of machines. In order to guard against an overestimation of this convertibility, nevertheless, resource elements were divided into subclasses by the size of the product, the seriality of production, and other relevant factors. The total number of individually defined resource elements within the major classes enumerated above was fifty-three.

In order to permit a capability analysis of the economy, the production of various branches of the machine building sector was represented by statistically determined weighted averages of the typical individual machines which were analyzed in the course of the study.

The "resource element" concept summarized above can be integrated easily with the Markowitz-Rowe approach, both in requirements analysis and in substitution analysis.

In the Soviet Machinery Industry study of the University of North Carolina, the resource-element concept is used in connection with a simple requirements analysis, and no substitution between resource elements is permitted. Employing the resource element rather than the individual machine as the basic building block of a *requirements analysis* has the following advantages:

1. It simplifies the collection of information and permits the reconciliation of fragmentary data. Intermediate concepts such as this may perhaps appear superfluous from a purely analytical point of view because they are eliminated from the analysis at a subsequent stage. In the present instance, for example, they disappear in the course of a matrix multiplication. Nevertheless, they can be highly useful in practice, since they often correspond to the categories under which the original information is easiest to collect. In addition, they permit the focusing of attention on a limited number of variables at a time, and thus they facilitate the recognition of basic connections among the data. Finally, they create broad classes of phenomena within which statistical regularities can reveal themselves, whereas in working with the unaggregated elements (e.g., coefficients of machine-hour inputs directly into a particular product) the data are often so scarce that any potential relationships between them are masked by the accompanying random variations.

The convenience of the resource element concept from this point of view is illustrated by the fact that in the Soviet Machinery Industry study, earlier attempts (University of North Carolina, 1956, 1958) to evaluate directly the material, labor, and equipment inputs to classes of individual machines have

met with serious difficulties, whereas the achievement of the same objectives in an indirect manner, through the intermediary of the resource element concept, has been successful and has permitted the compilation and organization of a large body of empirical information.

2. The resource element concept is a convenient means of bringing together statistical and engineering information. In the Soviet study, for example, the determination of resource element inputs into typical individual products within an industrial branch was undertaken principally by engineering techniques: the study of product blueprints, of shop layouts, equipment lists, and personnel classifications. All of this, however, was preliminary to the estimation of a weighted average of individual products for the purpose of representing the industrial branch as a whole, with the weights derived from statistical sources.

The methods used by Markowitz and Rowe¹ for deriving material, labor, and equipment input coefficients are based largely on Census data, and engineering estimates are suggested by the authors only for the purposes of secondary corrections. This method is useful and accurate in the case of structurally stable and well-studied economies, for example, the United States economy. Its applicability, however, becomes severely limited when *either* considerable structural change is taking place which renders statistical coefficients rapidly obsolete, or statistical data sources are scarce and unreliable, as is the case with all but a few countries (and more so with regions within countries). When working with underdeveloped economies, both structural instability and a lack of reliable data have to be contended with. In such situations, the combined engineering-statistical approach to requirements estimation, used in connection with resource elements, appears to be considerably superior to an attempt to transfer statistical information from one country for which it is available (e.g., the United States) to another country for which it is not.

It follows that for the purpose of most planning and locational studies in situations of development, where structural changes are of central interest, the combined engineering-statistical approach made possible by the resource element concept is likely to be superior to an approach based largely on statistical data.

3. The resource element concept, while maintaining the analytical techniques of ordinary requirements analysis, nevertheless introduces a considerable degree of flexibility into the investigation of capabilities, by allowing substitution between the *semifabricates* that can be obtained from a given resource element. Thus, the yearly capacity of a foundry or a forge, expressed in tons of semifabricate, is reasonably constant for pieces of equal general complexity and unit weight, produced under conditions of comparable average lot size. The great advantage of the resource element concept in this regard is that it takes care of the overwhelming majority of trivial substitutions between simple, standard metalworking machinery operations, by the elementary method of creating an aggregated concept. Thus, in the substitution analysis

¹ See also *Process Analysis of the Metalworking Industries*, Markowitz et al. (1953).

(to be discussed below), attention can be centered on a relatively small number of critical substitutions, without burdening the model with a profusion of detail.

The advantage of the flexibility achieved by means of the definition of resource elements is, however, obtained at the expense of some product-mix problems which invariably accompany the use of aggregative concepts. Thus, the capacity of a resource element varies with the average composition of its output, and so does the ideal adjustment between the number and kind of machines, the amount of floorspace, the numbers and skills of workers and the kinds and amounts of flow inputs which characterize each resource element. When the average complexity or lot size of the semifabricates changes within reasonably narrow limits, an acceptable approximation is possible by means of defining simple capacity corrections, similar to the corrections for non-standard tasks based on units of standard tasks in the Markowitz-Rowe substitution analysis. Nevertheless, this approximation does not allow for structural changes within the capacity and flow inputs of the resource elements. In order to improve the approximation substantially, it is necessary to increase the number of resource elements and to narrow the definition of each individual element. This brings the approach closer to ordinary requirements analysis as discussed by Markowitz and Rowe, but it increases the range of substitution that remains outside the confines of the individual resource elements.

A good compromise between the two objectives—flexibility on the one hand and homogeneity on the other—is afforded by the device of breaking out the specialized, outsize, or otherwise scarce items of machinery from the aggregated resource elements and handling them individually. This maintains the flexibility afforded by the substitution between common classes of machinery inside each resource element, but allows at the same time the identification of the major bottlenecks due to the limited capacities of individual machines during the course of the requirement analysis.

In regard to *substitution analysis*, the resource element concept appears at first sight in a somewhat ambiguous role. On the one hand, it can be regarded as a generalization of the “standard task” concept of Markowitz and Rowe. While geometry is not distinguished in defining resource elements, several of the other identifying dimensions (size class, precision, seriality) coincide between the Markowitz-Rowe *task* concept and the University of North Carolina *resource element* concept. On the other hand, a resource element can also be regarded as one of a set of differing “universal machines” each of which, in the University of North Carolina study, can perform but one single task. This ambiguity will be clarified in the discussion below.

While the Soviet Machinery Industry study contemplates no substitution possibilities between resource elements, this restriction is not necessary. In other words, the specification of one single input pattern of resource element units into a given product is not a built-in feature of the University of North Carolina method. On the contrary, it is logical to permit, for example, distinct resource elements which differ only in regard to seriality, to substitute

for each other; likewise, resource elements which differ only in regard to the size of the heaviest fabricate they can turn out may substitute for each other in neighboring size classes, completely in one direction and at least partially in the other.² Moreover, substitution possibilities exist between unrelated resource elements; e.g., forge and foundry, since they can produce closely substitutable fabricates by their distinct operations: e.g., cast versus forged crankshafts.

Substitution possibilities between resource elements are reflected by alternative input patterns of resource element units into production activities. From these alternatives, process analysis models can be constructed in the usual way.

In order to clarify the relationship between the various concepts referred to above, three linear programming models are presented in Tables 1-A through 1-C. The first summarizes the key features of the Markowitz-Rowe approach; the second refers to the approach used by the University of North

TABLE 1-A
INTERPRETATION OF MARKOWITZ-ROWE MODEL

Task generation ac- tivities based on machine classes					Production ac- tivities: one alternative			
	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	
1010 1090 9010 9090					0001 0008 0009			
0100 0900 0100 0900					0001 0001 0001			

CODE								Machine
Machine class								$b = (n) \cdot (u)$ availabilities
y 1000 0000	<i>a</i>	<i>a</i>					$b = (n) \cdot (u)$ by class*	
y 9000 0000			<i>a</i>	<i>a</i>				
Task								0 Task balances
y 0010 0000	-1		-1		<i>a</i>	<i>a</i>	<i>a</i>	
y 0090 0000		-1		-1	<i>a</i>	<i>a</i>	<i>a</i>	
Product								- <i>b</i> Product demands
y 0001 0000					-1			
y 0008 0000						-1		
	\geq	0	0	0	0	0	1	→ MAX
								↓ MIN

* Total machine availability in each machine class equals number of machines in the class times unit availability.

Explanation of code and other notes are given following Table 1-C.

² In other words, a heavier forging resource element can turn out all of the fabricates of the neighboring lighter element; while due to the fact that each forge handles a variety of fabricate sizes, many of which fall considerably short of the maximum, the lighter forge can also take over part of the work of the heavier forge.

Carolina; and the third is a general model from which both of the former approaches can be derived as special cases.

In *Table 1-A*, a coefficient *a* is given for the generation of each task by each machine:³ this permits the substitution of one machine for another in generating given total task requirements. On the other hand, only one task combination exists for the production of each product: in other words, there are no alternative production activities embodying alternative task combinations for given products. Thus, flexibility in the manufacturing of products is obtained only by the substitution of machines in the generation of tasks, not by the substitution of tasks in the production activities. Evidently, an easy generalization of this model is possible by introducing alternative production activities.

TABLE 1-B
INTERPRETATION OF UNIVERSITY OF NORTH CAROLINA MODEL

CODE	Resource element definition activities		Task generation by resource elements		Production activities			≤	
	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>		
	0100	0900	0100	0900	0001	0008	0009		
	1000	1000	0010	0010	0001	0001	0001		
Machine class									Total machine availabilities
<i>y</i> 1000 0000	<i>a</i>	<i>a</i>						<i>b</i> (not given)	
<i>y</i> 9000 0000	<i>a</i>	<i>a</i>						<i>b</i> (not given)	
Resource element									Resource element balances
<i>y</i> 0100 0000	-1		1					0	
<i>y</i> 0900 0000		-1		1				0	
Task									Task balances
<i>y</i> 0010 0000			-1		<i>a</i>	<i>a</i>	<i>a</i>	0	
<i>y</i> 0090 0000				-1	<i>a</i>	<i>a</i>	<i>a</i>	0	
Product									Product demands
<i>y</i> 0001 0000					-1			- <i>b</i>	
<i>y</i> 0008 0000						-1		- <i>b</i>	
	≥	0	0	0	0	0	1		→ MAX
									↓ MIN

Explanation of code and other notes are given following *Table 1-C*.

³ When a given machine is not capable of generating a specific task, the corresponding coefficient *a* can be made sufficiently great to prohibit the use of this activity in an optimal or near-optimal solution.

TABLE 1-C
GENERALIZED METALWORKING SUBSTITUTION MODEL

		Resource element definition activities				Task generation activities based on machine classes				Task generation activities based on resource elements				Production activities							
		<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>	<i>x</i>		
		0100	0100	0900	0900	1010	1090	9010	9090	0100	0100	0900	0900	0001	0001	0008	0008	0009	0009		
Code		1000	9000	1000	9000	0100	0900	0100	0900	0010	0090	0010	0090	0001	0009	0001	0009	0001	0009		
Machine class		<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>													Machine	
<i>y</i> 1000 0000		<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>															$b = (n) \cdot (u)$ availabilities by class*	
<i>y</i> 9000 0000		<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>			<i>a</i>	<i>a</i>												
Resource element		-1	-1							1	1									0 Resource element balances	
<i>y</i> 0100 0000				-1	-1							1	1								
<i>y</i> 0900 0000																					
Task						-1	-1			- <i>a</i>	- <i>a</i>	- <i>a</i>	- <i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	0 Task balances	
<i>y</i> 0010 0000								-1	-1	- <i>a</i>	- <i>a</i>	- <i>a</i>	- <i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>		
<i>y</i> 0090 0000										- <i>a</i>	- <i>a</i>	- <i>a</i>	- <i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>		
Product														-1	-1					- <i>b</i> Product demands	
<i>y</i> 0001 0000																-1	-1				
<i>y</i> 0008 0000																					
		≥	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	→ MAX
																				↓ MIN	

* Total machine availability in each machine class equals number of machines in the class times unit availability. Explanation of code and other notes are given on following page.

NOTES TO TABLES 1-A, 1-B AND 1-C

The tables have been formulated in synoptic notation showing the direct and dual problems simultaneously. The direct variables (x) of the upper margin, when multiplied by the lower margin, give the direct criterion function, to be maximized; when multiplied by the coefficients of each row, they give the direct constraints. The dual variables (y) of the left margin, when multiplied by the right margin, give the dual criterion function (to be minimized); when multiplied by the coefficients of each column, they give the dual constraints. Among the technical coefficients in the tables, the positive ones represent inputs, the negative ones, outputs.

In each of the three tables, the complete parametric linear programming problem is summarized by the maximization of the last product with the other products held constant; evidently, any product can be maximized or any primary input (machine class) minimized, or any linear combination of these optimized, within the rules of parametric programming problems.

All variables and parameters are identified by an eight-digit code shown on the upper and the left margins. The code of the upper margin applies to the entire column; that of the left margin, to the entire row. Internal parameters at the intersection of a row and column receive the code obtained by the consolidation of the row and column codes.

In each digit of the code, the first element of a series is indexed as 1, the last element, as 9, and the next to the last element, as 8. A code position not relevant for indexing an element is filled by 0. In the tables, only the first and the last element of each one-dimensional series is shown.

The coding is explained in the following tabulation:

Code for Tables 1-A, 1-B, and 1-C				
Digit	Commodities:	Activities:	Constraints	Other
	Dual variables (y)	Direct variables (x)		
1	Machine class	-	Total availability	n = total number of machines in a class u = unit availability of each machine in a class
2	Resource element	-	-	-
3	Task	-	-	-
4	Product	-	Fixed demand	-
5	-	Resource element definition	-	-
6	-	Task generation based on machines	-	-
7	-	Task generation based on resource elements	-	-
8	-	Production	-	-

Examples:

$x(0900\ 0010)$ denotes the first alternative way of generating tasks from the last resource element.

The coefficient a at the intersection of the row (0010 0000) and the column (0008 0009) represents the input of the first task in the production, by the last alternative method, of the next to the last product.

In *Table 1-B*, the University of North Carolina model is interpreted in linear programming terms. Resource elements are defined by specifying their contents of individual machines.⁴ There is only one way of defining each resource element. The same rigid description is applied to the manufacture of products: there is only one resource-element combination for the manufacture of each product.

In order to facilitate the subsequent generalization of this model, the concept of "task" has been introduced as a formal intermediate stage between products and resource elements. As seen in *Table 1-B*, each resource element has been associated with the output of a unique task. This task is quantified in terms of the output of semifabricate from a given resource element: thus, for example, a forge of a given size and seriality class performs the unique task of producing a specified number of yearly tons of its own class of forgings, assumed to be homogeneous.

This concept of a task is entirely analogous to the Markowitz-Rowe concept. The fact that a resource element, as mentioned earlier, at times appears as a generalization of the task concept, and at other times as a "universal machine," becomes now understandable considering that in the University of North Carolina study there is a one-to-one correspondence between resource elements and tasks. Thus, speaking of units of task inputs into the production of given products comes to the same thing in this model as speaking of units of resource element inputs. In generalized versions of the model, however, this will no longer be necessarily so.

As there are no joint outputs in the original version of the model, the latter is equivalent to a simple Leontief input-output model as long as there is no more than one restriction on primary inputs (machine availabilities).⁵ In fact, the original approach ignores maximization and starts with prescribed levels of *all* product demands (which at once determine the levels of production activities). This allows the derivation of resource element inputs, and, by a subsequent matrix multiplication, the computation of the levels of individual machine requirements. No limits are set on the latter.

In *Table 1-C*, a generalized model is given with four commodity classes: machines, resource elements, tasks, and products; and four classes of activities: the definition of resource elements, the generation of tasks by individual machines, the generation of tasks by resource elements, and the manufacture of products based on task inputs. The sets of activities are, however, generally more comprehensive than in the Markowitz-Rowe or the University of

⁴Floorspace and flow inputs, not shown in *Table 1-B*, are likewise rigidly specified.

⁵See Dorfman, Samuelson, and Solow (1958), Chapter 9.

North Carolina models. Thus, alternative definitions of each resource element are permitted, in order to take into account the variations in the machine parks of typical shops, either in response to different proportions of semi-fabricates, or in response to differing local conditions. Likewise, each resource element is assigned several alternative combinations of task outputs, in order to allow for variations in the proportions of different kinds of fabricates falling into the same general size, seriality, or other classification. Finally, the manufacture of each product is represented not by one activity, but by several activities specifying alternative task combinations.

The Markowitz-Rowe model can be derived from this more general model by suppressing resource elements and eliminating alternative production activities. This leaves only the substitution of machines in task generation as an element of flexibility in the model. The University of North Carolina model can be derived by ruling out task generation by individual machines, eliminating alternative resource element definitions, and cutting down the generation of tasks from resource elements to one task per resource element.

The general model itself, representing a synthesis between the two approaches, can be used in the following fashion:

1. All simple, common and usual-sized machines are grouped into *resource elements*, leaving only the special, outsize, or otherwise scarce machines as individual entities. Even in the latter cases, it appears desirable to group all ancillary equipment used with such machines into a single resource unit.

2. Preferably, one *definition of each resource element* is adopted as a standard; alternative definitions are best handled by means of a sensitivity analysis in the form of joint changes in groups of parameters. Such joint changes might be used, for example, to represent a systematic shift of the definition of all resource elements in the direction of greater self-sufficiency.⁶ If desired, nevertheless, alternative definitions may be left explicitly in the model.

3. In the case of individual machines, coefficients for the *generation of alternative tasks* are specified by the general model in the same way as by the Markowitz-Rowe model.

4. In the case of task generation by resource elements two alternative approaches are possible: *First*, a few typical alternative tasks may be associated with each resource element on the basis of common types of alternative fabricates falling into the same weight, size, or seriality class; subsequently, several alternative task generation activities may be specified for each resource element. These alternative activities differ in regard to the proportions of tasks generated by the resource element. *Second*, the one-to-one correspondence between tasks and resource elements may be retained. In this case, the task is regarded as a *standard task* in the sense of Markowitz-Rowe; it is taken to correspond to a given average composition of typical fabricates. Subsequently, requirements of fabricates in other proportions can be expressed in units of standard tasks, similarly to the Markowitz-Rowe formulation.

⁶A comparison of typical shops in the U. S. A. and the U.S.S.R. shows that the latter typically comprise a higher proportion of large and specialized equipment and machines needed for internal repairs and maintenance (A. D. Little, 1961).

5. Whichever way the generation of tasks by resource elements is handled, the effect of the lack of homogeneity in semifabricate outputs from resource elements is only partially overcome. It has been mentioned earlier that the machine park of a resource element may vary in response to different proportions of typical semifabricates. When a process analysis model comprises an ample range of alternatives in regard to resource element definitions as well as in regard to variations in the proportions of typical semifabricates produced by individual resource elements, the model itself can be expected to determine the optimal definitions of resource elements and the optimal proportions in the outputs of semifabricates. In practice, however, it is hard enough to find the empirical information for specifying even a single alternative in regard to each one of these dimensions of variation: thus, the issues of resource element definition and the average composition of semifabricate outputs generally have to be decided before the model is constructed, on the basis of whatever information, often of a qualitative nature, happens to be available concerning the particular problem in hand.

6. It is a matter of detail, without effect on the structure of the model, whether there is an overlap between the tasks capable of being generated by individual machines and those capable of being generated by resource elements. Whenever a given machine or resource element does not lend itself to the generation of a specific task, the corresponding input coefficient can be set at a prohibitive level without a loss of generality.

7. For the manufacture of each product (or for several products jointly) alternative activities comprising alternative task combinations are given.

The generalized model, when used according to the above observations, will *concentrate the analysis* on the identification of bottlenecks that may exist in specialized, outsize, or otherwise scarce machinery; on the substitution of different kinds of resource elements (forge, foundry, machining) in the manufacture of products; on the substitution of shops with different size, weight, precision, or seriality characteristics; and on the distribution of typical semifabricates produced by each resource element. By the techniques of sensitivity analysis, the effects of systematic shifts in resource element composition on the optimal solution of the model can also be explored; and when the data permit doing so, the model can determine optimal machine parks and optimal proportions of semifabricate outputs for resource elements. At the same time, substitutions between simple, common and standard-sized metalworking machines; e.g., between different kinds of machine tools in a machine shop, are handled *implicitly* by the definition of aggregative concepts: the concept of a resource element and the concept of a task generated by a resource element. Since in most practical studies the overwhelming majority of substitutions are of the latter type, the resulting economy of effort is considerable.

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