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PRIORITIZING INTERDEPENDENT PRODUCTION PROCESSES USING LEONTIEF INPUT-OUTPUT MODEL

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Abstract
This paper proposes a methodology in identifying key production processes in an interdependent production system. Previous approaches on this domain have drawbacks that may potentially affect the reliability of decision-making. The proposed approach adopts the Leontief input-output model (L-IOM) which was proven successful in analyzing interdependent economic systems. The motivation behind such adoption lies in the strength of L-IOM in providing a rigorous quantitative framework in identifying key components of interdependent systems. In this proposed approach, the consumption and production flows of each process are represented respectively by the material inventory produced by the prior process and the material inventory produced by the current process, both in monetary values. A case study in a furniture production system located in central Philippines was carried out to elucidate the proposed approach. Results of the case were reported in this work.

Keywords
manufacturing process, process prioritization, input-output model, interdependent production system.

Introduction

Manufacturing firms nowadays strive not only to survive but also to remain competitive in their respective industries. To sustain competitiveness, managers must be critical in various decision-making areas. Decision-making is a crucial process that requires a complex integration of multiple sources of information in order to produce outcomes beneficial to the respective industry in general and to the firm in particular [1]. At firm level, several aspects such as technology selection, supplier selection, production planning and control, inventory management, workforce management, quality management, and process prioritization must be considered [2].

Effective production management is said to deal with technological complexities [3]. These refer to the complexity of the entire system caused by the innovations of manufacturing products and processes. Moreover, processes possess inherent interactions which are difficult to understand such that independently controlling process variables for individual process would fail to optimize overall production system [3]. Due to these complex relationships, process prioritization is highly important which must be viewed from a systems perspective. This is significant as it aids organizations in resource allocation decision, human resource planning, strategy formulation, inventory management, among others [4]. One particular industry that is characterized by process complexities is furniture manufacturing since it manufactures products of wide variety which are customized depending on customer preferences and specifications [5]. Various interrelated processes are needed in making high quality and intricately designed furniture pieces which require management to exert more emphasis on resource allocation.

Several approaches on process prioritization have been proposed in literature. Famous tools are analytic hierarchy process (AHP) and failure mode evaluation analysis (FMEA), among others. See [6] for the application of these methods in process prioritization. Generally, these methods involve qualitative and subjective data based on some value judgments of decision-makers. These may lead to incorporating biases which may potentially affect the reliability of decision-making. Thus, there is a need for a quantitative approach in process prioritization that relies on hard data in order to produce a more reliable decision.

Following this need, this study attempts to adopt the Leontief input-output model (L-IOM) that aims to quantitatively aid manufacturing decision-makers at firm level in prioritizing interdependent processes. Developed by Wassily Leontief in 1936 who later won a Nobel Prize in Economic Sciences, L-IOM is a macroeconomic tool which was successfully used to analyze interdependent economic systems [10]. L-IOM reveals a promising approach in process prioritization because it can address relationships or interdependencies of system components, originally for sectors within an economy. L-IOM was also able to address how changes in one system component, say an economic sector, affect other economic sectors through a flow of goods in a closed-loop system. The relevance of L-IOM in process prioritization is that it is capable of identifying key system components along with the mutual interactions of other components. It has been widely adopted for interdependency analysis of sectors at a macro level, country-level, and even on a local level [11].

This paper aims to apply L-IOM in the context of analysing interdependencies of processes in manufacturing process systems with the goal of identifying key processes. The research problem that is advanced in this paper can be formally stated as follows: Given a set of interdependent processes in a production system, which process or processes must be on top priority and be given with particular attention? While former approaches provide insights on this research problem, they fail to provide a quantitative analytical framework which is highly significant in providing a more reliable decision-making. A case study of a process system in a furniture manufacturing firm is reported in this work. The contribution of this study is presenting a new methodological framework that holistically addresses process prioritization at firm level.

This paper is organized as follows. The next section provides a review on current approaches in production process prioritization. It also presents the overview of the basic L-IOM, its foundations, issues and model formulation. The required procedure in carrying out the proposed method is then presented. A case study in a furniture manufacturing firm is then discussed where the proposed method is applied. Results and findings are highlighted. Finally, this paper ends with a conclusion and a discussion of practical insights.

Literature review

Prioritization of interdependent processes

Manufacturing industries at present are becoming highly dynamic that managers need to be more critical in decision making in order to sustain competitiveness of the organization. Reference [12] have identified the stages in the evolution of the strategic role of manufacturing firms. Manufacturing firms start of as adapters to the outside forces that influence them and as they advance, manufacturing units eventually exert efforts to be the drivers of change. Maintaining this competitiveness of an industry entails effective decision-making. Reference [1] highlighted that decision making is a dynamic process that requires complex integration of multiple sources of information to produce outcomes. Decision-making in manufacturing industry includes several areas such as technology selection, supplier selection, production planning, production control, inventory management, workforce management, quality management, and process prioritization, among others [2].

Reference [3] argued that effective management of production in a factory deals with technological complexities. These technological complexities relate to how complex the system and its technologies, i.e. for both products and processes, become. Processes possess inherent interactions which are difficult to understand such that independently controlling process variables for individual process cannot optimize overall production system. For instance, small changes in materials, surroundings, and day-to-day procedures can impact the entire production process beyond expected [3]. With these complex relationships, one cannot immediately prioritize a particular process without considering other processes. Following this notion, one must view process prioritization as a systems approach.

Several approaches have been adopted by industries and organizations to carry out strategic decisions in process prioritization. Two famous tools in this area include analytic hierarchy process (AHP) and failure mode evaluation analysis (FMEA). AHP, developed by [13], has been widely used as a multi-criteria decision-making tool to aid managers in choosing the alternative that best satisfies their goal. Reference [14] used AHP to prioritize manufacturing sectors and as well as establish priorities for energy management improvement. AHP was also used in facility location selection and supplier selection problems [6]. Reference [15] combined AHP with multi-objective linear programming (MOLP) as an approach to prioritize competitive strategies towards sustainable business. Other studies include the applications of AHP in total quality management and flexible manufacturing systems [16]. FMEA is a methodology used in assessing the criticality of potential failure modes within a system by correlating these failure modes to their effects. This tool calculates risk prioritization numbers, based on the failure's likelihood of being undetected and severity of its effects that help decision-makers prioritize processes with respect to their potential failures [8]. FMEA was used for optimization of process parameters in a case of a process industry [17].

These two approaches for process prioritization revolve around qualitative measures that are subjective based on some value judgments of decision-makers. The subjectivity used in these approaches induces biases in coming up with a decision which may lead to lesser reliability. Hence, in order to properly address certain issues, quantitative tools must be preferred. The use of quantitative data as input to the approach used in decision-making will certainly lead to more reliable results. Measures on process prioritization need to be accurate so that the best decision is chosen and more appropriate actions are taken. From a systems perspective, process prioritization is important for decision-makers in order for them to properly decide which process should be given more importance without compromising other processes, e.g. in terms of resource allocation [4].

Leontief input-output model

Input-output (IO) model developed by Wassily Leontief in 1941, originally intends to address how changes in one economic sector may have an effect on other sectors. In this regard, it generally portrays the relationships among the sectors of an economy. L-IOM combines production data of different sectors comprising an entire economy. It shows the required amount of a sector's production when its output is consumed by final consumers and by other sectors as raw materials for their own production. Generally, the model developed by Leontief is a demand-driven analysis wherein it is more concerned with how the entire system will be affected when demand changes [11].

L-IOM shows the relationship between sectors of an industry through a simple yet so monumental linear equation also known as the Leontief balance equation:

$$x = Ax + c, \qquad (1)$$

where x is an $n \times 1$ vector containing the production output of n sectors, A is an $n \times n$ interdependency of sectors, known as IO coefficients, expressed as a proportion of the sector's values of inputs with respect to its output, c is the $n \times 1$ vector of final demand.

The flow of goods, particularly inputs and outputs,in monetary terms are recorded in an IO table as in Table 1.

Table 1
Input-output model [11].

		Buying sector					Exogenous final demand (c)	Required production (x)
		1	⋮	j	⋮	n		
Selling sector	1	o_{11}	⋮	o_{1j}	⋮	o_{1n}	c_1	x_1
	⋮	⋮		⋮		⋮	⋮	⋮
	i	o_{i1}	⋮	o_{ij}	⋮	o_{in}	c_i	x_i
	⋮	⋮		⋮		⋮	⋮	⋮
	n	o_{n1}	⋮	o_{nj}	⋮	o_{nn}	c_n	x_n
Value added		v_1		v_2		v_3		
Total inputs (y)		y_1		y_2		y_3		

The terms o_{ij} represent interindustry outputs of sector i, also known as intermediate sales, consumed by other sectors j, including itself, when $j = i$ for the production of their own goods [11]. Value-added shown in Table 1 signifies external products/services utilized by the different sectors. Technological matrix A can be obtained by dividing individual elements o_{ij} by the total inputs y. In addition, as a basic rule of L-IOM, total inputs y must be equal to the required production x.

Given the matrix A and an identity matrix I, the vector of required outputs can be calculated by rewriting (1) into:

$$x = (I - A)^{-1}c. \tag{2}$$

The matrix $(I-A)^{-1}$ of (2) is widely known as the Leontief inverse and is often regarded to as the total requirements matrix (TRM). This matrix may be a straightforward one; yet it is considered to be one of the powerful strengths of the IO model. Identification of the key sectors is done through the TRM [18]. Once $(I - A)^{-1}$ is obtained, the total output multiplier is calculated by adding the column values of each sector. The largest total output multiplier value corresponds to the key sector(s).

Monetary vs. physical input-output model

IOM has been widely used in macroeconomic analyses which were generally constructed using monetary input-output table (MIOT) [19]. Reference [20] highlighted that a monetary input-output table records all transactions made within an economy in terms of money such as billion dollars and it has been widely used to analyze the impacts of economic policies to all sectors found in an economy. Several extensions have been made to L-IOM but majority of IO case studies conducted until the 90's were utilizing MIOTs perhaps due to the lack of data on intersectoral transactions [19].

IO tables have been applied in the context of economic analysis; however, they have been increasingly utilized for environmental impact assessments which account to the construction of input-output tables in terms of mass units hence, the emergence of physical input-output table (PIOT) [19]. The primary function of PIOT is to serve as an economic-environmental accounting framework. [21]. Reference [22] highly suggested PIOT for the quantification of direct and indirect resource requirements. Thus, its importance is acknowledged by environmental, resource, and energy economies [20]. PIOT compiles the flows of physical products, acquisition of raw materials from nature, supply and use of wastes, and emissions to nature and stock changes. It compiles these data in terms of physical units such as million tons.

Reference [21] have stated advantages of PIOT which include its application of the mass balance principle thus homogenization of classification schemes and data collection methods is attained and its ability to validate and or improve the existing MIOT because it highlights a different dimension of the same economy. Even though PIOT is a better reflection of a sector's use of another sector's product, it entails substantial measurement problems when sectors actually produce various products [11].

L-IOM is greatly known in macroeconomic applications however, this framework is not only limited to economic sectors alone. Table 2 provides a sum-

Table 2
Number of products undergoing each process.

Classification		References	Explanation
Environment-related applications	energy	[24]	applied input-output to analyse demand and consumption of energy
	water	[29, 30]	studied the reallocation of water and its effects on the other sectors if one sector changes its consumption
	mining	[31, 32]	explored the application of input-output models in mining industries. Specifically, it estimates the impact of increased mining activity
	emissions	[33]	applied input-output to analyse the corresponding emission in fulfilling the final demand
Materials flow		[23, 34]	used input-output to trace the flow of materials from the formation of say, metal until it is being used
Economic-related applications		[35]	applied input-output to analyse how a congested port affects the whole economy
Services		[36]	used input-output analysis in determining the required time a library personnel must accomplish his task upon servicing the library users and upon doing his other library duties

mary of the applications of IO. Note that this list is not intended to be comprehensive. It is therefore applicable to other areas that consider a system composed of elements such as processes in production systems for instance. These processes generate output that becomes an input to its succeeding process in order to convert semi-finished product into finished product. Consequently, production processes establish interrelationships among themselves making the entire system interdependent. Some attempts have been made to incorporate IOM in production processes [23] but its applicability in process prioritization specifically has not been explored in current literature. The proposed IO model in this study retains the structure and mathematical foundation of the L-IOM but instead of dealing with economic systems, evaluation of manufacturing process systems is considered.

Methodology

Data requirements

Generally, the required data set to complete the IO table are as follows: (i) the detailed flow of processes, (ii) the flow of materials, specifically the input and output inventory from one process to another, and (iii) the corresponding costs of these materials. MIOT is used in this work since production processes may have multiple product varieties and combining them homogeneously is rather difficult. Thus, data are in terms of monetary values of the input and output inventories. To collect these data, the following steps are taken: (i) obtain the amount of materials from one process to another from the Production and Planning Control Department, (ii) collect data from the accounting department to determine the corresponding monetary values of the products that are used and produced by each process.

General procedure

The general procedure of the proposed framework is detailed as follows:

1. Translate the obtained monetary transactions into matrix A.
2. Compute the production output vector x using (1).
3. Compute the Leontief inverse using (2).
4. After computing for the Leontief inverse, obtain the column sums. The corresponding production process with the largest column sum is considered as the most important process.

Case study

A case study was conducted in Firm X which is one of the top furniture companies in the country and an internationally recognized manufacturing firm that produces a wide variety of furniture products at the premium quality. Firm X, situated in Cebu City, Philippines, distributes stylish furniture pieces globally.

Manufacturing its furniture products involves 13 different processes. This furniture firm has fairly similar processes used in any production floor since wood is the commonly used material in the industry. However, innovations have been made as portrayed by the uniqueness and intricate design of current furniture products. These innovations pave way to new processes. Firm X has been offering various unique furniture products. It incorporates natural materials to its innovative handmade production. The following are the firm's processes in the manufacturing its products: milling, assembly, fiber/stone casting, metal framing, powdercoating, weaving, retouching, sanding, finishing, upholstery, final fitting, final quality check and final packing process.

Figure 1 presents the general process flow for each product. It is observed that products do not go through the same set of processes. Figure 2 shows a graph of the number of products that are transformed through each manufacturing process. The volume of products manufactured by the firm for the current year 2015 has a total of 183 units and all of these products undergo final fitting, final quality check, and final packing while the least utilized process is fiber/stone casting.

Figure 3 shows the total costs of materials for each production process. It can be observed that packing process has the greatest cost compared to other processes. From the management perspective, the hypothesis is that in the context of process prioritization, the firm's management considers packing as the most important process as it involves the largest cash flow.

The argument highlighted in this work is that in prioritizing processes, it is not enough to analyse process in isolation but instead take into consideration the interdependencies of all processes. This paves way to the utilization of L-IOM in process prioritization.

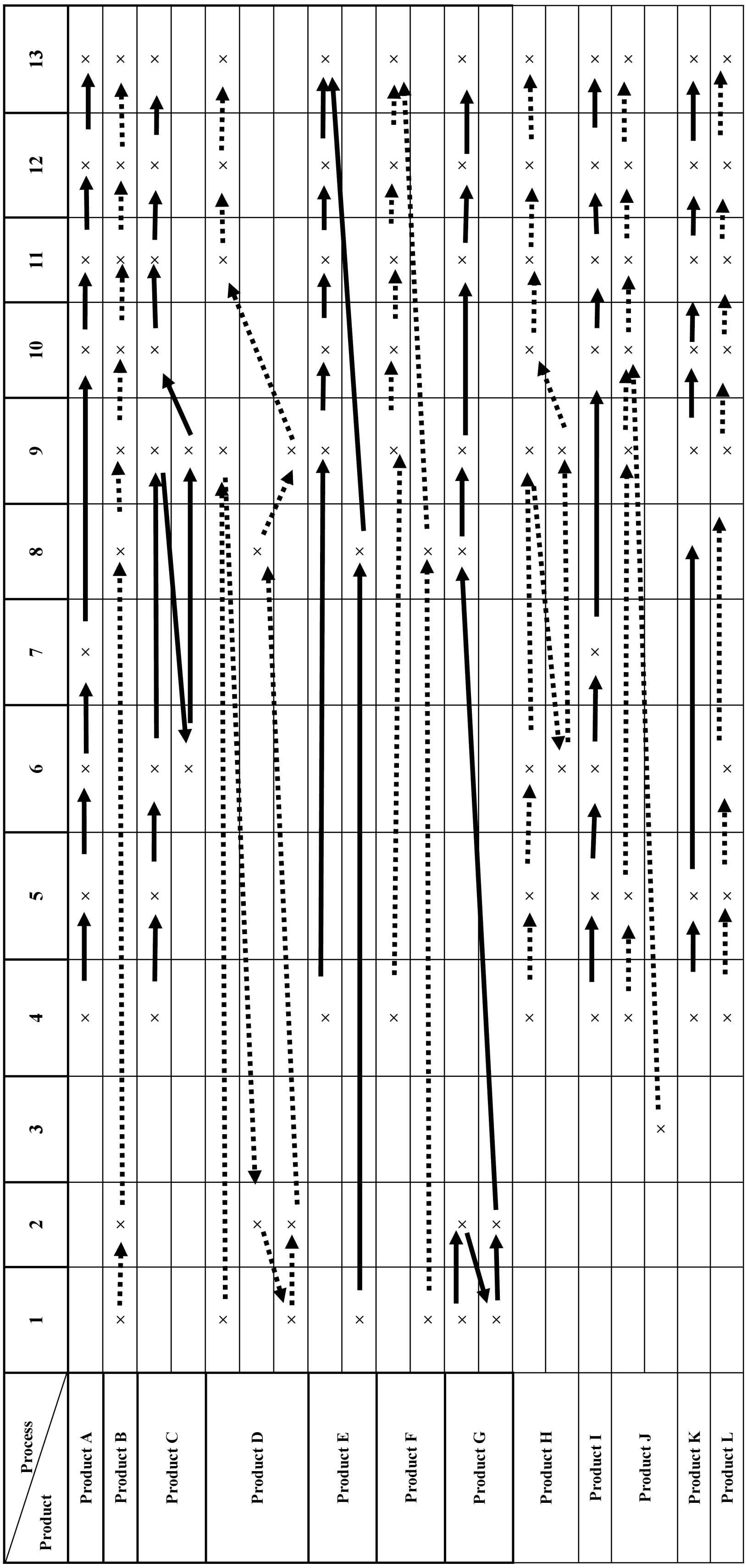

Fig. 1. General process flow for each product.

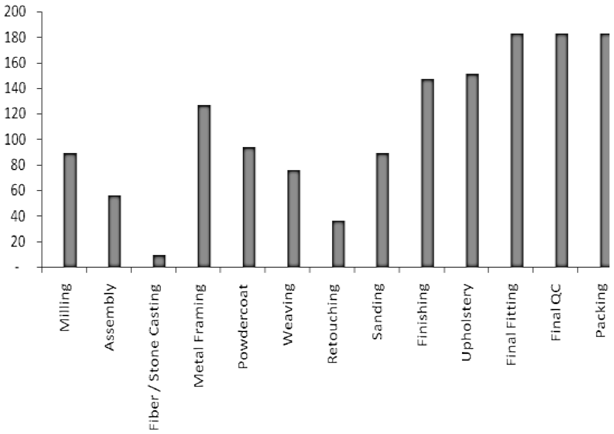

Fig. 2. Number of products undergoing each process.

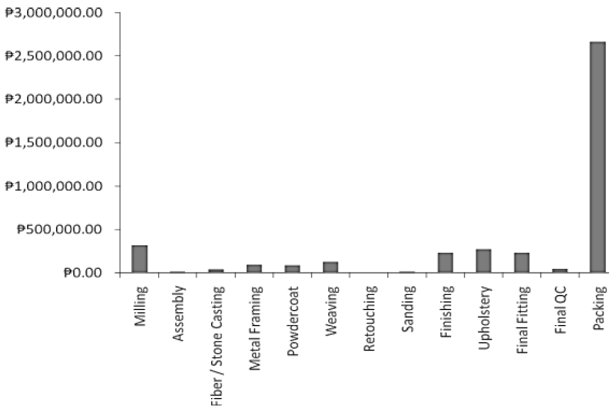

Fig. 3. Total material cost for each process.

Results and discussion

After adding all corresponding costs associated with the input and output of each process in the case firm, the IO table is generated in Table 3.Unlike economic IO tables, the IO table in Table 3 generated for a firm-level analysis is not entirely filled-up as some values are zeros. This is case specific as the processes involved in the firm depend solely on the type of product being produced and not all products undergo the same set of processes due to the customized nature of the furniture design as per customer preference.

The values obtained in the IO table are normalized as shown in Table 4. These values represent the proportion which each process consumes with respect to its output. These values are less than 1 since additional materials, which is reflected in the 'value-added' row, are needed in order to further transform it with the use of other processes. The Leontief inverse is obtained using (2) and indicates values that are factors of final demand in determining the required production as shown in Table 5. After obtai-

Table 3
Input-output table of Firm X.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	Exogenous Demand (c)	Required Output (x)
[1] Milling	–	945,897.64	–	–	–	–	–	27,600.00	108,540.00	–	–	–	–	–	1,082,037.64
[2] Assembly	143,272.52	–	–	–	–	–	–	933,753.27	–	–	–	–	–	–	1,077,025.79
[3] Fiber/Stone casting	–	–	–	–	–	–	–	–	–	38,008.08	–	–	–	–	38,008.08
[4] Metal framing	–	–	–	–	63,177.93	–	–	–	25,298.65	–	–	–	–	–	88,476.58
[5] Powdercoating	–	–	–	–	–	73,778.01	–	–	71,671.05	–	–	–	–	–	145,449.06
[6] Weaving	–	–	–	–	–	–	98,894.84	–	152,582.26	–	–	–	–	–	251,477.10
[7] Retouching	–	–	–	–	–	–	–	–	–	102,494.84	–	–	–	–	102,494.84
[8] Sanding	–	–	–	–	–	–	–	–	936,033.63	–	–	–	37,813.60	–	973,847.23
[9] Finishing	–	116,109.86	–	–	–	54,306.45	–	–	–	558,864.76	817,215.58	–	–	–	1,546,496.65
[10] Upholstery	–	–	–	–	–	–	–	–	–	–	961,176.30	–	–	–	961,176.30
[11] Final fitting	–	–	–	–	–	–	–	–	–	–	–	2,005,323.05	–	–	2,005,323.05
[12] Final quality check	–	–	–	–	–	–	–	–	–	–	–	–	2,048,314.33	–	2,048,314.33
[13] Packing	–	–	–	–	–	–	–	–	–	–	–	–	–	4,765,659.26	4,765,659.26
Value Added	938,765.12	15,018.29	38,008.08	88,476.58	82,271.13	123,392.64	3,600.00	21,325.96	275,571.06	339,515.32	307,149.89	138,448.39	2,821,890.04	–	–
Total Inputs	1,082,037.64	1,077,025.79	38,008.08	88,476.58	145,449.06	251,477.10	102,494.84	982,679.23	1,569,696.65	1,038,883.00	2,085,541.76	2,143,771.44	4,908,017.97	–	15,085,785.89

Table 4
Technological coefficient matrix.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
[1] Milling	–	0.88	–	–	–	–	–	0.03	0.07	–	–	–	–
[2] Assembly	0.13	–	–	–	–	–	–	0.95	–	–	–	–	–
[3] Fiber/stone casting	–	–	–	–	–	–	–	–	–	0.04	–	–	–
[4] Metal framing	–	–	–	–	0.43	–	–	–	0.02	–	–	–	–
[5] Powdercoating	–	–	–	–	–	0.29	–	–	0.05	–	–	–	–
[6] Weaving	–	–	–	–	–	–	0.96	–	0.10	–	–	–	–
[7] Retouching	–	–	–	–	–	–	–	–	–	0.10	–	–	–
[8] Sanding	–	–	–	–	–	–	–	–	0.60	–	–	–	0.01
[9] Finishing	–	0.11	–	–	–	0.22	–	–	–	0.54	0.39	–	–
[10] Upholstery	–	–	–	–	–	–	–	–	–	–	0.46	–	–
[11] Final fitting	–	–	–	–	–	–	–	–	–	–	–	0.94	–
[12] Final quality check	–	–	–	–	–	–	–	–	–	–	–	–	0.42
[13] Packing	–	–	–	–	–	–	–	–	–	–	–	–	–

Table 5
Total requirements matrix (Leontief inverse).

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
[1] Milling	1.14	1.08	–	–	–	0.16	0.15	1.06	0.73	0.41	0.47	0.44	0.19
[2] Assembly	0.16	1.22	–	–	–	0.16	0.15	1.16	0.72	0.40	0.47	0.44	0.19
[3] Fiber/stone casting	–	–	1.00	–	–	–	–	–	–	0.04	0.02	0.02	0.01
[4] Metal framing	0.00	0.01	–	1.00	0.43	0.14	0.13	0.01	0.05	0.04	0.04	0.04	0.02
[5] Powder coating	0.00	0.01	–	–	1.00	0.31	0.30	0.01	0.08	0.07	0.07	0.06	0.03
[6] Weaving	0.00	0.01	–	–	–	1.02	0.99	0.01	0.11	0.15	0.11	0.11	0.04
[7] Retouching	–	–	–	–	–	–	1.00	–	–	0.10	0.05	0.04	0.02
[8] Sanding	0.01	0.08	–	–	–	0.14	0.14	1.08	0.66	0.37	0.43	0.40	0.17
[9] Finishing	0.02	0.13	–	–	–	0.24	0.23	0.13	1.10	0.61	0.71	0.67	0.28
[10] Upholstery	–	–	–	–	–	–	–	–	–	1.00	0.46	0.43	0.18
[11] Final fitting	–	–	–	–	–	–	–	–	–	–	1.00	0.94	0.39
[12] Final quality check	–	–	–	–	–	–	–	–	–	–	–	1.00	0.42
[13] Packing	–	–	–	–	–	–	–	–	–	–	–	–	1.00
Total output multiplier	1.34	2.57	1.00	1.00	1.43	2.16	3.09	3.46	3.45	3.19	3.82	4.58	2.94
Rank	**11**	**8**	**12**	**12**	**10**	**9**	**6**	**3**	**4**	**5**	**2**	**1**	**7**

ning the Leontief inverse, an output multiplier for each process can then be obtained. Total output multiplier takes into account the total change in the output required of processes caused by a change in 1 unit of demand for that specific process.

Results from Table 6 show that final quality checking process ranks first in the priority ranking followed by final fitting and sanding processes. Despite of the relatively smaller costs incurred in final quality checking, this process must be on top priority of the case firm. This may be because that all products regardless of variety go through the final quality checking process such that inoperability of this process may affect largely the entire production system. This result implies that more priority must be given to this process which may be in terms of investments, materials, resources and labor. The management can use the results of the IO as bases for their process prioritization and improvement plans since it shows how processes are utilized in terms of the inflow and outflow of materials.The management can also allocate resources to other processes depending on their rank as shown in Table 6.

Table 6
Process ranking.

Process	Total Output Multiplier	Ranking
Milling	1.34	11
Assembly	2.55	8
Fiber / stone casting	1.00	12
Metal framing	1.00	12
Powdercoating	1.43	10
Weaving	2.16	9
Retouching	3.09	6
Sanding	3.46	3
Finishing	3.45	4
Upholstery	3.19	5
Final fitting	3.82	2
Final quality	4.58	1
Packing	2.94	7

Conclusion

This work highlights a methodology in holistically identifying key processes in a production system. Previous approaches in this problem domain relied largely on some methodologies that are based on subjective judgments which may be insufficient in making reliable decisions. In this paper, a Leontief input-output model was proposed to use in process prioritization. The relevance of this model is its capability in addressing interdependent system which is an inherent characteristic of most manufacturing systems. While previous methods utilized soft data, the proposed model applies hard data, i.e. the consumption and production of materials from one process to the other. This approach simulatenously considers production processes as a system rather than isolating each process for analysis.

To elucidate the proposed approach, an actual case study was carried out in a furniture manufacturing firm in central Philippines – previously known as the hub in furniture exports. Thirteen processes were analyzed and results show that the final quality check must be a priority process followed by final fitting and sanding. Being the first priority, management might conduct planning to brainstorm possible actions that must be carried out in improving final quality check process. Management could now have a more indepth look on the current final quality check process along with salient aspects such as its labor allocation, equipment, and other resources in order to plan out specific improvement activities. The priority ranking of processes obtained from this paper can be used by the case firm management as an input to decision-making such as in resource allocation planning, human resource planning, strategy formulation, etc. This would enable the management come up with an overall plan of improving its processes.

In general, the main findings suggest that using the Leontief input-output model, production process prioritization could be objectively generated. This paper reports a novel approach in process prioritization that takes into account the complexity of material flows in a typical production system. The proposed approach is methodologically simple that can be easily subscribed by practicing managers yet provides a powerful quantitative framework in identifying key processes in interdependent production systems. Due to the objectivity of the proposed approach, practitioners could then benefit from eliminating biases and subjectivity; thus, ensuring that the decision is reliable.

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