Modularity and Integrability-based Energy Minimization in a Reconfigurable Manufacturing Environment: A Non-linear Mixed Integer Formulation

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Abstract: Nowadays, manufacturing environment is characterized by the necessity of customized flexibility as well as responding rapidly and cost-effectively to changing market demands while minimizing impacts on environment and society. To reach these goals, a key paradigm called sustainable manufacturing can be coupled with reconfigurable manufacturing systems (RMSs). The coupling of RMS characteristics and sustainability concerns is a basis to develop a new generation of sustainable production systems. This paper outlines sustainability in a reconfigurable environment from an energy consumption point of view. A non-linear mathematical model is developed to optimize the energy consumption of a RMS through a redefinition of its core characteristics—modularity and integrability. The objective is to minimize the energy consumption of the system by selecting the most suitable modular machines from a set of candidate machines. The optimization problem is addressed using an exhaustive search heuristic. Finally, the applicability of the proposed approach is illustrated through a simple numerical example and the discussion of the obtained results.

Keywords: Sustainability; reconfigurable manufacturing system; modularity; integrability; sustainable manufacturing; process planning; energy consumption.

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1. INTRODUCTION

Sustainable manufacturing is a new paradigm in which manufacturing industries produce products in a sustainable manner while maintaining global competitiveness (Battaïa *et al.*, 2020). Hence, today's manufacturing systems are faced with a new challenge: how to accommodate requirements of sustainability? Moreover, traditional manufacturing systems —such as dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS)—are unable to adapt to face the dynamic market demand, the requirement products variety, the short product lifecycle and the changes in process technology require. In this context, reconfigurable manufacturing systems (RMSs) are a logical development of the two traditional manufacturing systems and are designed to combine high flexibility of FMS with the high production ratio of DMS. Koren *et al.* (1999) defined RMS as "*a key to survive in the new manufacturing environment characterized by highly competitive market and the necessity of companies to be able to react to changes rapidly and cost-effectively*.

On the other hand, today's global market also faces an increasingly complex environment due to people's conscious and strict regulations in matter of sustainability, the scarcity of natural resources, the global warming and the emergence of greenhouse gases emissions challenges. The publication of Our Common Future in 1987 gave the most commonly used definition of sustainable development as `meets the needs of the present without compromising the ability of future generations to meet their own needs'. In response to the growing sustainability concerns, companies must formulate some measures to evaluate sustainable performance. The goal is to integrate within the manufacturing environment, indicators of the three aspects of sustainability namely environmental, social and economic, known as the triple bottom line of sustainability.

Manufacturing systems must be, simultaneously, cost-effective, time-efficient and environmentally harmless (Battaïa *et al.*, 2020). In this scenario, RMS seems to match these manufacturing requirements. Although nowadays both sustainability and responsiveness are more urgent and relevant issues than ever, few studies focus on both reconfigurability and sustainability. Consequently, there is a need of models and technique to evaluate if and how RMSs enhance sustainability through its reconfigurability and its core characteristics.

In this research work, we address the environmental sustainability issue from an energy consumption point of view. The goal is to design an RMS taking into account it energy consumption minimization. Although energy consumption and environmental impact is related to only one of the three pillars of sustainability, environmental evaluation of RMSs is a useful starting point. In this regard, RMS is assessed in terms of energy consumption starting from the definition of its core characteristics. Hence, it is possible to assess other aspect of sustainability. More specifically, we consider two of the six RMS core characteristics as a starting point namely modularity and integrability. A mathematical model is developed to quantify both characteristics in terms of energy consumption. Our model considers interfaces, controllers as well as basic and auxiliary modules. In this way, the reconfigurability of the RMS and the impact of the implementation of its characteristics on the environment are evaluated simultaneously.

The rest of the paper is organized as follow: Section 2 provided a briefly review of related works to RMSs its core characteristics (especially modularity and integrability) and research works on sustainable manufacturing. Section 3 presents the considered problem and the mathematical formulation. Section 4 details the proposed approach. Section 5 shows an illustrative numerical example and derails the obtained results. Section 6 concludes the paper with some future research directions.

2. LITERATURE REVIEW

The concept of RMS was proposed at the end of 1990s by Professor Koren as a system which can rapidly change in structure, as well as in hardware and software components, in order to provide the exact functionality and capacity as and when required (Koren *et al*., 1999). This goal is achieved through the six key characteristics of RMSs that are modularity, integrability, convertibility, scalability, customization and diagnosability. Modularity, integrability and diagnosability help in achieving the RMS conversions efficiently in terms of reconfiguration time and effort. In this regard, many studies attempted to quantify reconfigurability characteristics (Bortolini *et al*., 2018).

It is well known that, modularity is addressed as one key characteristics of RMSs and integrability is measured in terms of effort required to integrate each degree of freedom into the rest of the system. Hence, Wang *et al.* (2017) developed quantitative models for all the characteristics of an RMS at multiple levels (machine tools and units). Modularity is analysed in terms of module granularity and module interfaces of the machine tool and of the system, while integrability is analysed in terms of software/hardware interface adjustment time and cost that are in inverse relation to the integrability of RMS. The authors used an integrated AHP method and two-phase PROMETHEE method to achieve a comprehensive evaluation of the alternative reconfiguration schemes.

Most recently, focus on characteristics moved from a static to a dynamic vision to reach high level of reconfigurability of the system while considering classical objectives such as minimizing cost and time. In this context, Haddou Benderbal *et al.* (2018) proposed a multi-objectives approach to optimize the RMS design. Authors consider three objectives to guide the design namely maximizing system modularity and minimizing the system completion time and cost. They developed a modularity index that quantifies the designed system modularity based on its selected machine and the product family evolution. The optimization problem is solved using an adapted version of the well-known metaheuristic named archived multi-objective simulated annealing (AMOSA). Wang *et al.* (2019) proposed a systematic methodology for setting modules of reconfigurable machine tools (RMTs). RMTs are characterized by an adjustable structure using basic and auxiliary modules, which allow to expand the set of feasible operations. Starting with a classification of conceptual modules, the method allows the creation of functional module group of RTMs following structural and functional characteristics of the components that construct the machine tools, the geometry modules and the basic structure modules.

When it comes to sustainability at manufacturing level, the U.S. department of commerce defines sustainable manufacturing as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound”. Hence, manufacturing environment is faced with three main challenges related to the three pillars of sustainability. Garbie (2013) developed a sustainability index (SI) that is the mathematical expression of designing for sustainable manufacturing enterprise (DFSME). It is based on seven major aspects among which we can find RMSs, manufacturing strategies, performance measurement and flexible organization management. In more microscopic view, Garbie (2014) proposed a comprehensive framework of sustainable development based on the three dimensions: economical, societal and environmental. He presented full analytical and quantitative models and developed an index to balance the three dimensions. Huang et al. (2017) presented a metrics-based methodology for an enterprise sustainability index (EnSI). The EnSI evaluates sustainable manufacturing performance at the enterprise level. More recently, Huang et al. (2018) considered simultaneously the three pillars of sustainability and total product lifecycle as well as the ability to implement the 6Rs (rethink, refuse, reduce, reuse, recycle, replace). The study selected the characteristic of RMS ‘convertibility’ as an example to assess impacts on sustainable manufacturing performance as it changes.

According to Wang *et al.* (2013), the industrial sector is the largest consumer energy and emitter of greenhouse gases. For this reason, literature related to energy in production systems have flourished in recent years. Choi *et al.* (2015) proposed a production planning model on a LP with the multi-objective function for minimizing the energy consumption and maximizing the throughput. A methodology to estimate energy consumption and material flows is defined from a process plans perspective for RMS. Ghanei *et al.* (2016) suggested a linear mixed integer mathematical model to configure the manufacturing system. The goal is to make it more efficient and maximize its sustainability. They computed the consumed energy for each configuration in an RMS using a holistic production planning approach. The approach considers three factors: the change pattern in energy prices during a day, the transportation cost of jobs moving from one machine to another and the setup cost of each machines. Touzout *et al.* (2019a) proposed a multi-objective optimization sustainable process plan generation for a single unit product in a reconfigurable environment. Their approach was guided by three criteria’s namely cost, time, and amount of the GreenhouseGas emission (GhG). As an extension, Touzout *et al.* (2019b) developed a sustainable multiunit process plan generation problem in RMS. Authors considered as new additional criterion to their previous work machine’s exploitation time. In the same context, Khezri *et al.* (2020) considered the multi-objective single-product process plan generation problem in RMS, where energy consumption is used as one of the criteria to minimize.

Nowadays, manufacturing systems must be energy efficient, minimize their environmental impacts while being responsive. Moreover, metrics to investigate the level of sustainability of RMSs are of great importance (Huang *et al.*, 2018). Yet and to the best of our knowledge, little research work is done to integrate sustainability as a design objective of RMS. More specifically measures/metrics that couple RMS core characteristics through redefining them in terms of energy consumption are rarely considered. In this context, our paper considers two of the main characteristics of RMSs namely modularity and integrability. The two characteristics are modelled by considering the energy consumption in their definition. The objective is to minimize the energy consumption of the RMS.

3. PROBLEM DESCRIPTION AND FORMULATION

3.1 Problem description

Modularity is the "compartmentalization of operational functions into units that can be manipulated among alternate production schemes for optimal arrangements" (Bortolini et al., 2018). In an RMS, reconfigurable machine tools (RMT) are modular and are considered as a key component. In our case, we consider a set of candidates modular RMTs, where each machine m comprises a set of configurations NC. RMTs comprise two types of modules, auxiliary modules AM, which represent the reconfigurable part and can be changed, added and removed (i.e., adapter plates and spindle heads), and basic modules BM, which represent the fixed part of each configuration c in a given machine m (i.e., slide ways, bases and columns). The energy consumption considers the use of basic modules, and assembling and disassembling auxiliary modules for each configuration as well as the changing machine consumption.

Integrability is "the ability to connect modules rapidly and precisely by a set of mechanical, informative and control interfaces facilitating integration and communication" (Bortolini et al., 2018). In this context, our model considers (i) the controllers of each module, e.g., programmable logic controller (PLC) and (ii) the interfaces between them.

In this paper, we consider the problem of process plan generation for a single unit of a product to be manufactured. Table 1 shows a simple example of a process plan.

Table 1. Illustrative structure of a process plan

Operation	OP1	OP3	OP4	OP2
Machine	M6	M2	M1	M4
Configuration	C2	C4	C3	C1
Basic Module	BM1, BM2	BM2	BM3, BM4	BM3
Auxiliary Module	AM4, AM5, AM6	AM2, AM3	AM2	AM2, AM4

The product comprises a set of operations TNOP to be achieved. Each operation can be processes by different RMTs with different configurations. In order to integrate modules, a number of interfaces are evaluated for each configuration of machines $NI_{m,c}$ that are proportional to the number of total modules (*BM*+*AM*) - 1.

3.2 Problem formulation

Table 2 details the used notations and decision variables.

Table 2. Notations and decision variables

Indices	
Operations	o, o' =1, ..., TNOP
Configurations	c, c' = 1, ... , NC
Machines	m, m' = 1, ..., NM
Basic modules	γ = 1, …, BM
Auxiliary modules	δ =1,..., AM
Parameters	
TNOP	Total number of operations
NC	Total number of configurations
NM	Total number of machines
BM	Number of basic modules
AM	Number of auxiliary modules
SMAC	Set of available machines
SCN	Set of configurations
$NI_{m,c}$	Number of interfaces
$PRM_o^{o'}$	Precedence Matrix
$E_{PLC}^{m,\gamma}$	Energy consumption by controller PLC of γth basic module on the mth machine
$E_{PLC}^{c,\delta}$	Energy consumption by controller PLC of δth auxiliary module for the cth configuration
E_{WASTE}	Energy waste between interfaces
$E_{CHANGE}^{m,m'}$	Energy changing machines
$E_{ASS}^{c,\delta}$	Energy consumption by assembling δth auxiliary module for the cth configuration
$E_{DIS}^{c,\delta}$	Energy consumption by disassembling δth auxiliary module for the cth configuration
$E^{m,\gamma}$	Energy consumption by γth basic module on mth machine
Decision variables	
$w_o^{m,c}$	1 if the oth operation is being processed by the mth machine using cth configuration, 0 otherwise
$\mathrm{x}_{\mathrm{o},\gamma}^{\mathrm{m,c}}$	1 if the mth machine is using the γth basic module in cth configuration for the oth operation, 0 otherwise
$y_o^{m,m'}$	1 if there has been a change between machine m and m' in the oth operation, 0 otherwise
$\mathrm{u}_{\mathrm{o},\delta}^{\mathrm{m,c}}$	1 if the mth machine is using the δth auxiliary module in cth configuration in the oth operation, 0 otherwise
$z_{o,\delta}^{m,c}$	1 if the δth auxiliary module is assembled on the mth machine in cth configuration in the oth operation, 0 otherwise
$v_{o,\delta}^{m,c}$	1 if the δth auxiliary module is disassembled on the mth machine in cth configuration in the oth operation, 0 otherwise

Objective function

Objective (1) represents the total energy consumption (TEC) function to be minimized. It includes two parts. The first concerns the energy consumption for integrability (ECI) depicted by (2). The second concerns the energy consumption for modularity (ECM) depicted by (3).

$$\min TEC = ECI + ECM \tag{1}$$

where:

$$ECI = \sum_{o=1}^{TNOP}\sum_{m=1}^{NM}\sum_{c=1}^{NC}\left\{\left(w_o^{m,c} * \sum_{\gamma=1}^{BM} x_{o,\gamma}^{m,c} * E_{PLC}^{m,\gamma}\right) + \left(w_o^{m,c} * \sum_{\delta=1}^{AM} u_{o,\delta}^{m,c} * E_{PLC}^{c,\delta}\right) + \left(w_o^{m,c} * NI^{m,c} * E_{WASTE}\right)\right\} \tag{2}$$

$$ECM = \sum_{o=1}^{TNOP}\sum_{m=1}^{NM}\sum_{c=1}^{NC}\left\{\left(w_o^{m,c} * \sum_{m,m'\in SMAC} y_o^{m,m'} * E_{CHANGE}^{m,m'}\right) + \left[w_o^{m,c} * \left(\sum_{\delta=1}^{AM} z_{o,\delta}^{m,c} * E_{ASS}^{c,\delta} + \sum_{\delta=1}^{AM} v_{o,\delta}^{m,c} * E_{DIS}^{c,\delta}\right)\right] + \left[w_o^{m,c} * \sum_{\gamma=1}^{BM} x_{o,\gamma}^{m,c} * E^{m,\gamma}\right]\right\} \tag{3}$$

The following equations detail the model constraints:

$$PRM_o^{o'} = 0 \qquad \forall\, o > o',\ o, o' = 1, .., TNOP \tag{4}$$

$$\sum_{m=1}^{NM}\sum_{c=1}^{NC} w_o^{m,c} = 1 \qquad \forall o = 1, ..., TNOP \tag{5}$$

$$z_{o,\delta}^{m,c} + v_{o,\delta}^{m,c} = u_{o,\delta}^{m,c} \qquad \forall o = 1, ..., TNOP, \forall m = 1, ..., NM, \forall c = 1, ..., NC, \forall \delta = 1, ..., AM \tag{6}$$

Constraint (4) states that each operation should respect the precedence constraints. Constraint (5) considers each operation processes just one time. Constraint (6) states that same auxiliary module can't be assembled and disassembled in same operation on the same machine and for the same operation.

4. PROPOSED APPROACH

Based on the previously described energy minimization model, a heuristic method is used to solve our optimization problem and generate process plans.

As shown in the flow chart of Fig. 1, first, we generate all possible combinations of operation sequences (*N*) that respected the precedence constraints (*i.e.*, feasible solutions). A big number is set as an initial value of the minimum energy consumption Emin (*e.g.*, the sum of all energy consumption of all candidate machines times 2). Then, the *N* sequences of operations are explored one by one, for each one, all the possible sequences of machines and corresponding configurations are generated. The energy consumption En is computed using equation (1). At this stage, the sequence of machines with minimum value of energy consumption is selected and compared with the initial value. The heuristic explores and evaluates all the possible solutions (process plans) and rank them based on the energy consumption value. The procedure end when all the sequences of operations are explored. The best sequence of operations and the best sequence of machines as well as the needed auxiliary and basic modules are those corresponding to the minimum value of energy consumption stored as Emin.

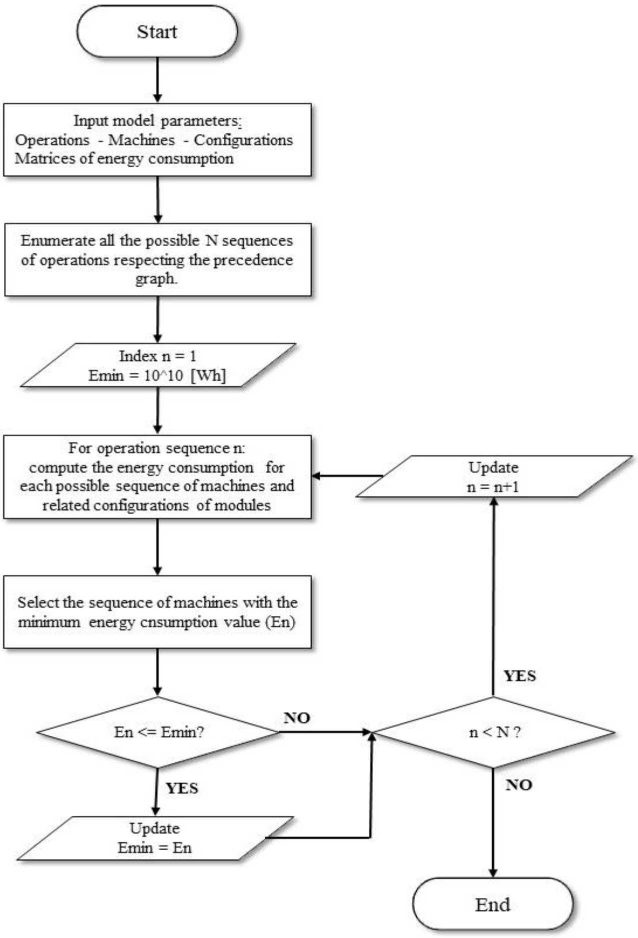

Fig. 1. Flow chart of the proposed heuristic

5. ILLUSTRATIVE NUMERICAL EXAMPLE

In this section, a simple numerical example is presented. It is implemented in MATLAB R2019b on a pc with the following configuration: (i) Core i5 and 2.40Ghz processor (ii) 8 GB RAM.

We consider a single unit of a product to be manufactured composed of six operations (OP) that can be processed by five different machines (M). An RMS module library is reckoned with three basic modules (BM) and seven auxiliary modules (AM). Figure 2 shows the precedence graph required for the product. Table 3 details the candidate machines and their configuration for each operation.

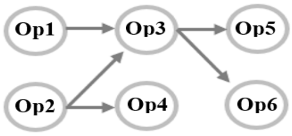

Fig. 2. Precedence graph

Table 3. Operation requirements

Operations	Machines	Configurations
Op1	M1	C1
	M5	C2
Op2	M2	C2
	M3	C3
	M4	C2
Op3	M1	C3
Op4	M1	C1
	M2	C2
	M3	C3
	M4	C3
	M5	C1
Op5	M2	C1
	M3	C2
	M1	C3
Op6	M1	C2
	M5	C1
	M4	C3
	M2	C2

Table 4 shows the specifications of candidate machines.

Table 4. Candidate machine specifications

Machines	Conf.	Basic Modules	Auxiliary Modules	Interfaces
M1	C1	BM1, BM3	AM1, AM2, AM3	4
	C3		AM1, AM2, AM7	4
M2	C1	BM2, BM3	AM3, AM5	3
	C2		AM6, AM7	3
	C3		AM2, AM5, AM6	4
M3	C3	BM1	AM4	1
M4	C1	BM2, BM3	AM5, AM6	3
	C2		AM2, AM4, AM5	4
	C3		AM1, AM7	3
M5	C1	BM1	AM3, AM4	2
	C2		AM2, AM5, AM6	3
	C3		AM2, AM3, AM4, AM6	4

Tables 5, 6 and 7 display respectively the energy consumption (EC) by basic modules, by assembling and disassembling auxiliary modules and the energy for changing machine in Wh (values based on the works of Simoneau *et al.,* 2013 and Choi *et al.,* 2015). Values of energy consumption by PLC and energy waste for airleaks between interfaces are based on AlGeddawy *et al.* (2016) works.

Table 5. Energy consumption of basic modules BM (Wh)

	M1	M2	M3	M4	M5
BM1	3672	-	3522	-	3934
BM2	-	3812	-	3976	-
BM3	4000	3623	-	3587	-

Table 6. EC for assembling/disassembling auxiliary modules

	AM1	AM2	AM3	AM4	AM5	AM6	AM7
Assembling (Wh)							
C1	1325	1268	1303	1270	1274	1268	1292
C2	1257	1206	1278	1315	1337	1257	1333
C3	1300	1317	1321	1292	1331	1275	1258
Disassembling (Wh)							
C1	1350	1310	1271	1233	1330	1260	1334
C2	1274	1204	1218	1294	1281	1258	1291
C3	1252	1287	1344	1314	1258	1299	1272

Table 7. Energy consumption for changing machine (Wh)

	M1	M2	M3	M4	M5
M1	3592	3976	3663	4080	3917
M2	3908	3511	4319	4046	3675
M3	4237	4085	3673	4467	3729
M4	3886	4144	3668	4157	4360
M5	3550	4320	4474	4200	3644

Tables 8, 9 and 10 present the obtained process plans and their TEC in Wh. We select the first two best solutions and a worst solution that has the same operation sequence as our best two solutions. Even though we have the same sequence of operations, the TEC is mainly affected by the selected machines, configurations of auxiliary and basic modules, and related interfaces. Moreover, the higher number of changing of machines between operations is the higher value of TEC of the system will be. Hence, minimizing the TEC firstly is affected by the selection of the best set of machines for each operation that minimize energy consumption by minimizing the number of machines changes between operations.

Table 8. Process plan for the best solution

OP	OP2	OP4	OP1	OP3	OP5	OP6
M	M3	M3	M5	M1	M1	M5
C	C3	C3	C2	C3	C3	C1
AM	AM4	AM4	AM2, AM5, AM6	AM1, AM2, AM7	AM1, AM2, AM7	AM3, AM4
BM	BM1	BM1	BM1	BM1, BM3	BM1, BM3	BM1
Total Number of Interfaces: 13						
Total Energy Consumption (TEC): 27372 Wh						

Tables 8 and 9 show that less energy consumption (EC) can be reached by smaller number of interfaces between modules. Moreover, modularity of machines has a positive impact on EC, when keeping the same machine between Op1 and Op3 (*i.e.*, the EC is only evaluated in terms of disassembling auxiliary module 3 and assembling auxiliary module 7).

Table 9. Process plan for the second-best solution

OP	OP2	OP4	OP1	OP3	OP5	OP6
M	M3	M3	M1	M1	M1	M5
C	C3	C3	C1	C3	C3	C1
AM	AM4	AM4	AM1, AM2, AM3	AM1, AM2, AM7	AM1, AM2, AM7	AM3, AM4
BM	BM1	BM1	BM1, BM3	BM1, BM3	BM1, BM3	BM1
Total Number of Interfaces: 16						
Total Energy Consumption (TEC): 27435 Wh						

Table 10. Process plan for a worst solution

OP	OP2	OP4	OP1	OP3	OP5	OP6
M	M2	M5	M5	M1	M2	M4
C	C2	C2	C2	C3	C1	C3
AM	AM6, AM7	AM2, AM5, AM6	AM2, AM5, AM6	AM1, AM2, AM7	AM3, AM5	AM1, AM7
BM	BM2, BM3	BM1	BM1	BM1, BM3	BM2, BM3	BM1
Total Number of Interfaces: 17						
Total Energy Consumption (TEC): 42810 Wh						

6. CONCLUSIONS

In this paper, we addressed the problem of sustainable process plan generation to design a RMS. Sustainability and reconfigurability are evaluated simultaneously by integrating energy consumption while modelling two core characteristics of RMS namely "*integrability*" and "*modularity*". We proposed a non-linear mathematical model through to formulate the problem. The process plan generation was guided by minimizing the total energy consumption of the system. To solve the problem, we developed a heuristic. As a result, the minimum value of energy consumption can be addressed by balancing the number of changing machines and the number of assembling and disassembling auxiliary modules between operations. For future works, we aim to develop a multi-objective approach by considering manufacturing criteria's such as cost and time. Moreover, an extension to include the rest of the other RMS characteristics in the model is possible.

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