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Gozintographs for By-Products and Cyclic Production: An Approach for ERP System Application

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Abstract

Cyclic production, which is distinctive of recycling and chemical processes, and by-products can hardly be managed in common ERP systems. This problem is discussed using graph representations like gozintographs. Furthermore an approach is presented to handle by-products and cyclic production with common gozintograph structures for acceptable solutions in the material requirements planning (MRP). For ERP application appropriated data structures are proposed. A discussion of benefits and limitations of the approach conclude the contribution.

Keywords: Analytic production, bill of materials, by-products, cyclic production, ERP, MRP, gozintographs

Common Gozintograph Structures in ERP Systems

Gozintographs are graphical representation of production structure of industrial manufacturing. They describe the quantitative relationships of raw materials, intermediate products, and end products. In Enterprise Resource Planning systems (ERP systems) the information about raw materials, intermediate products, and end products are stored in the material master database, the quantitative relationships are handled by the bills of materials management.
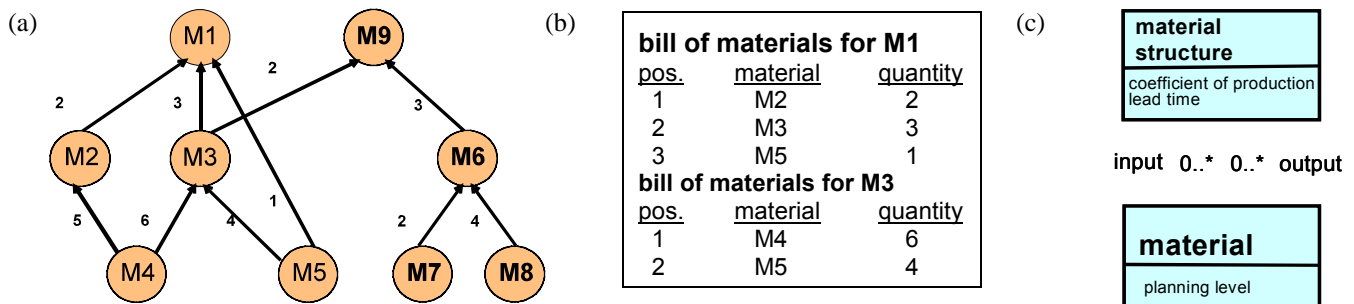

Figure 1. (a) Gozintograph, (b) Bills of Materials, and (c) Corresponding Class Diagram

Figure 1a shows a gozintograph with nine materials. Two materials (M1 and M9) are end products while M4, M5, M7, and M8 are raw materials. The edges between the materials represent the production structure. The example contains ten of such relationships. The numbers depicted at the edges are coefficients of production (CP) indicating the amount (e.g. CP = 2) of component (e.g. M2) required to make one unit of the resulting material (e.g. M1). The bills of materials for the products M1 and M3 are depicted in Figure 1b. They are tabular representations with position, subordinated material (input), and required quantity (CP) of the respective part of the gozintograph. In Figure 1c the corresponding data structure is shown in a UML class diagram as they are common for material management in ERP systems (Scheer 94, Hay 96). Instead of storing adjacency-lists or an adjacency-matrix, the nodes or vertices are represented as *material* class and the edges are represented as *material structures* association class forming a recursive association between two instances of *material*. Coefficients of production are an attribute

of *material structure*. The class diagram may be extended by an own class *bill of materials*, but the basic pattern, namely the recursive structure, is the same (Loos 97).

Common applications of bill of materials processors will be found in manufacturing industries for which synthetic production processes are typical. In synthetic production processes, one or several materials represent the input while only one material stands for the output, i.e. the production process causes a convergent material flow. On an assembly line several components like gearwheels, axles, a casing, and a casing cover are input materials while the gearbox is the single output material. In Figure 1a Material M4 through M7 might be the exemplary components, while M1 and M9 are different types of finished gearboxes. The materials M2, M3, and M6 are intermediate products like mounted axles. Thus, the edges of the directed graph of the gozintograph have the following semantics:

- Several incoming edges (like edges M3-M9 and M6-M9 into M9) are logical AND-connected, since all input materials are needed for the production process in the ratio of the coefficient of production.
- Several outgoing edges have to be interpreted as logical OR-connected (like M4-M2 and M4-M3 out of M4), since the input material (M4) is used for the production of each output. Regarding one single unit of quantity of a material, the outgoing edges are XOR-connected, since this unit can be used only for one of the possible graph targets (one unit of quantity of M4 can be used either to produces 0.2 units of M2 or it can be used, together with 0.66 unit of M5, to produce 0.166 units of M3).

Graphs for Analytic Production

In analytic production processes one input material is processed to several output materials at the same time, i.e. the production process causes a divergent material flow. Since the simultaneous yield of different materials is mandatory, the resulting materials are called by-products or co-products, depending of the economical status of the joint output. In Figure 2a input and output materials of an analytic production process are shown. M3 is processed yielding output material M1 and M2 simultaneously. Due to the mandatory simultaneity of the output the outgoing edges of M3 in the graph are logical AND-connected. Therefore the graph in Figure 2a is not a gozintograph in common sense but will be called analytic graph. In analytic production the perspective of economical consideration are usually contrary to the synthetic production. The perspective in synthetic production is backward from end product to raw material, i.e. from output to input. Therefore the coefficient of production (CP) is defined as units of quantity input material per unit of quantity output material. However, in analytic production the perspective is forward. For the ratio in the example in Figure 2a it would be more common to say that one unit of quantity of M3 is produced to 0.8 unit of quantity of M1 and to 0.2 unit of quantity of M2. This output per input ratio is reciprocal to the coefficient of production and called analytic coefficient of production (ACP). The ACP is depicted on the right side of the edges in Figure 2a, the CP is depicted on the left side.
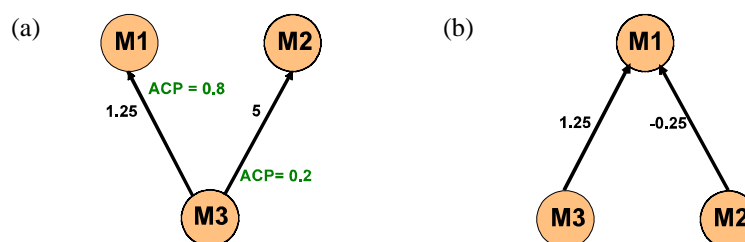

Figure 2. (a) Analytic Graph, and (b) Adjusted Graph with NCP

Analytic production is typical for industries processing raw materials which are directly obtained from nature, e.g. processing of oil, coal, and ore processing, slaughterhouse industries, dairy industries, and timber-based industries. It is also common in various fields in chemical industries. Strictly speaking most of the production processes have analytic characteristics, since they have more than one output. Apart from the desired end product mostly some waste is produced simultaneously, e.g. waste material, waste heat, or garbage. If this output is of low economic relevance, it is not regarded in ERP systems. But often these different types of output have relevance, either as revenue if it can be sold or as costs in case of waste disposal. A ranking of output according to the economic relevance could look like:

- co-production (several equivalent main products, good output),
- by-production (main products and sub-products, good output),

- cost-neutral output, and
- waste (bad output).

Gozintograph Application with Negative Coefficient of Production

So, how can analytic production be depicted with gozintographs? A first approximate solution can be done without modifying the semantic of the gozintograph. In this solution one output material is regarded as the single product, the other output materials as negative input (Luber 92). This is applicable with by-products, where only one output material is the main product while the others are economically subordinated. Assuming this is the case in the introduced example, a depiction is shown in Figure 2b. M1 is the main product while M2 is a by-product. M2 stands for the input to M1 with a negative coefficient of production (NCP). So, if one unit of M1 should be produced, 1.25 units of M3 and –0.25 units of M2 are needed. The negative coefficient of production is computed as:

$$NCP_{\text{by-product} - \text{main-product}} = -(CP_{\text{remaining-input} - \text{main-product}} / CP_{\text{remaining-input} - \text{by-product}}).$$

Since the two incoming edges in the adjusted graph in Figure 2b are logical AND-connected, the graph is indeed a gozintograph. The resolution of analytic structures works also with mixed analytic-synthetic production. Figure 3a shows an example with two input materials and two simultaneous output materials. Notice that this graph is not a gozintograph in common sense. Figure 3b represents the corresponding gozintograph under the condition that M1 is the main product and M2 is only a by-product.
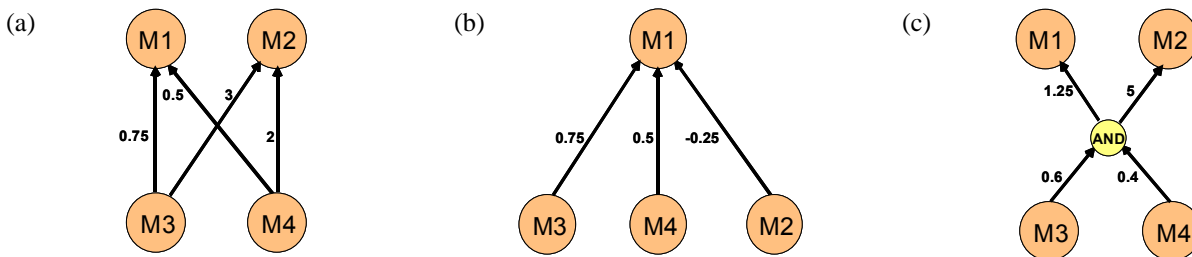
Figure 3. (a) Mixed Analytic-Synthetic Graph, (b) Adjusted Graph with NCP, and (c) Connector-Coded Graph

Connector-Coded Graphs

In the second solution the analytic production is explicitly modeled. To distinguish the different semantics of incoming edges or of outgoing edges, an second type of nodes is introduced carrying the respective semantic, so-called connector nodes (for further representations refer e.g. Duncan 83, and Loos 97). They are marked with logical predicates like AND, OR, or XOR. This type of connector-coded nodes are intuitively understandable and well known from other directed graph based representations like the network planning technique GERT, the business process notation event-driven process chain (EPC) and UML's activity diagram. Figure 3c gives an impression by showing the example of Figure 3a as a connector-coded graph. The semantic of the edges is unambiguous. It would be possible to extend the graph with further materials like a third end product M5, which is an alternate output of a second synthetic process combining M3 and M4. This extension could not be modeled in same mixed analytic-synthetic graph of Figure 3a, but could be modeled in the same gozintograph of Figure 3b. On the other hand, the connector-coded graph of Figure 3c has not the restriction that one of the output materials has to be determined as a main product and can therefore be applied with co-production of several equivalent main products.

Graphs for Cyclic Production

Cyclic production is characterized by the phenomenon that process output material is also input material to the same production process. Materials with cyclic flow in production processes are for instance catalyst, supplies and auxiliary materials, which are added to support chemical reaction, and waste materials that are recycled and added to the same type of production process (so-called primary recycling). It is apparently simple to represent cyclic production in gozintographs. Another edge is added to the graph defining the output material as an additional input material. This leads to a loop or recursion in the graph. In Figure 4a material M1 is output of a synthetic process with input materials M2 and M3. However, M1 is also input material to produce M2.

The length of a loop is defined as the number of contained material nodes. The simplest loop contains only one material node, a so-called self-loop. Figure 4a contains a loop with the length of 2. Cyclic gozintographs can be depicted in common data structures like in Figure 1c.
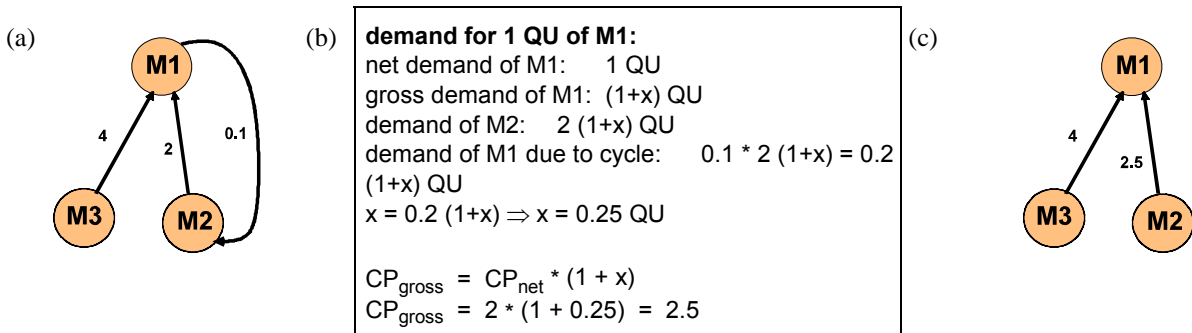
(a)   (b)   (c)

demand for 1 QU of M1:
net demand of M1: 1 QU
gross demand of M1: (1+x) QU
demand of M2: 2 (1+x) QU
demand of M1 due to cycle: 0.1 * 2 (1+x) = 0.2 (1+x) QU
x = 0.2 (1+x) $\Rightarrow$ x = 0.25 QU

$$CP_{gross} = CP_{net} * (1 + x)$$
$$CP_{gross} = 2 * (1 + 0.25) = 2.5$$

Figure 4. (A) Cyclic Gozintograph, (b) Calculation, and (c) Adjusted Graph with Cycle Elimination

Nevertheless, the problem occurring with cyclic graphs is their algorithmic processing. The information of bills of materials are used in several calculations by ERP systems, e.g. in MRP and in product cost calculations. The common algorithm for material requirements planning for instance processes the materials according to the bills of materials from the end products to the raw materials. Therefore all materials are sorted according to so-called planning levels (ref. Figure 1c). From the perspective of gozintograph the planning level of a material is its topological order according to a topological sort. The algorithm traverses the graph according to the topological order. Cyclic gozintographs would not allow a topological sort, and without topological order (planning level) common MRP does not work. Thus edit functions in bills of materials management in ERP systems usually check for cycles and preclude them.

For cyclic gozintographs a method has been developed to allow material requirement planning in the common manner (Müller-Merbach 66). Therefore the cyclic graph is converted in a acyclic (non-cyclic) graph. The cycle is broken up by eliminating the cycle-causing edge and recalculating the coefficients of production. For the cyclic gozintograph of Figure 4a the method is shown is Figure 4b. The method distinguishes between the net quantity of M1 as effectively required output quantity and the gross quantity of M1, which contains the quantity x flowing back as input into the process. The solution for x is provided by the equation shown in upper part of Figure 4b. In Figure 4a the edge M2-M1 is showing the net coefficient of production ($CP_{net} = 2$). In Figure 4c the same edge is showing the gross coefficient of production ($CP_{gross} = 2.5$). This CP_{gross} contains the quantities caused by the edge M1-M2 with CP = 0.1 of the graph of Figure 4a eliminated in the graph of Figure 4c.
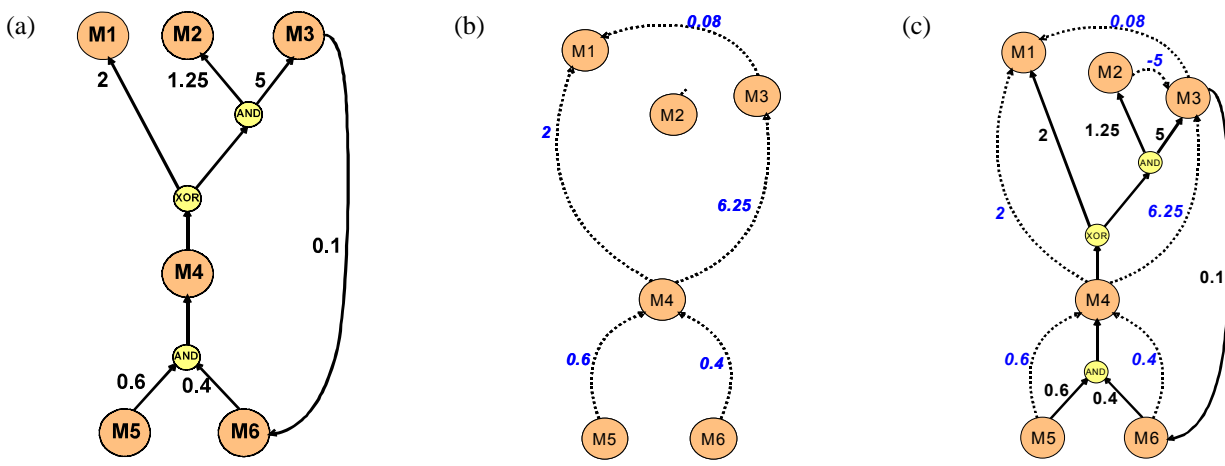
(a)   (b)   (c)

Figure 5. (a) Mixed Analytic-Synthetic-Cyclic Graph, (b) Adjusted Graph, and (c) Double-Coded Graph

In a more complex graph, the cycle elimination process has an impact to the other parts of the graph (Loos 97). The elimination has no impact on material of the graph before the cycle (before in the sense of topological order) and for material inside the cycle. But for material yielding as output out of the cycle, some relations may be cut by the elimination of the cyclic edge. This is true for the relation between M3 and M1 through the path M3-M6-M4-M1 in the example of Figure 5a. Therefore an additional edge M3-M1 is inserted to describe this relationship. The respective coefficient of production is the multiplication of coefficients of production of the old path (i.e. CP of M3-M1 is $0.1 * 0.4 * 2 = 0.08$). There is no need for an additional edge M3-M2 in the material relation of the path M3-M6-M4-M2, since M3 and M2 are due to their analytic character logically AND-connected and the additional material quantity is already considered in the CP_{gross} (=6.25) of M4-M3.

Proposed Application in ERP Systems

It has be shown that common gozintographs are not powerful enough to handle analytic and cyclic production. With a more enriched graph, the connector-coded graph, both issues can be handled and the representation is easy to understand. On the other hand, common algorithms, which have to handle huge quantities of data in practice, cannot run directly on a connector-coded graph. There are methods to convert the connect-code graphs in common gozintographs, so the common algorithms can handle the bills of materials.

For that reason an application is proposed that looks like this:

- Bills of materials should be managed by users in an easy way to use with connector-coded graphs using a graphical inter-face (Loos and Scheer 94). Analytic coefficients of production should be allowed.
- A conversion to an adjusted graph by eliminating cycles and analytic structure should be done by the system automatically.
- Both graphs are visible for users. An appropriated representation called double-coded graph is shown in Figure 5c.
- Both graphs are stored in the database of the ERP

Figure 6. Class Diagram for Double-Coded Graph

system using a data structure as shown in the class diagram of Figure 6 for example. Extending the structure of Figure 1c the class *node* is a complete and disjoint generalization of the classes *material* and *connector*. Instances of the association class *material structure* are either edges of the original connector-coded graph (*type = connector*, i.e. M4-XOR in Figure 5a), edges of the adjusted gozintograph (*type = adjusted*, i.e. M5-M4 in Figure 5b), or edges of both graphs (*type = both*, none in this example). The integrity constraint <1> in the note assures that every connector has at least one incoming and one outgoing edge and that the edge type is *connector* or *both*. Constraint <2> excludes cycles only on connectors but allows cycles if a material is involved in the cycle.
- The algorithms of applications like MRP and cost-calculation employ the information of the simplified adjusted graphs while other applications like routing and work schedule management can be based on the detailed information of the connector-coded graph.
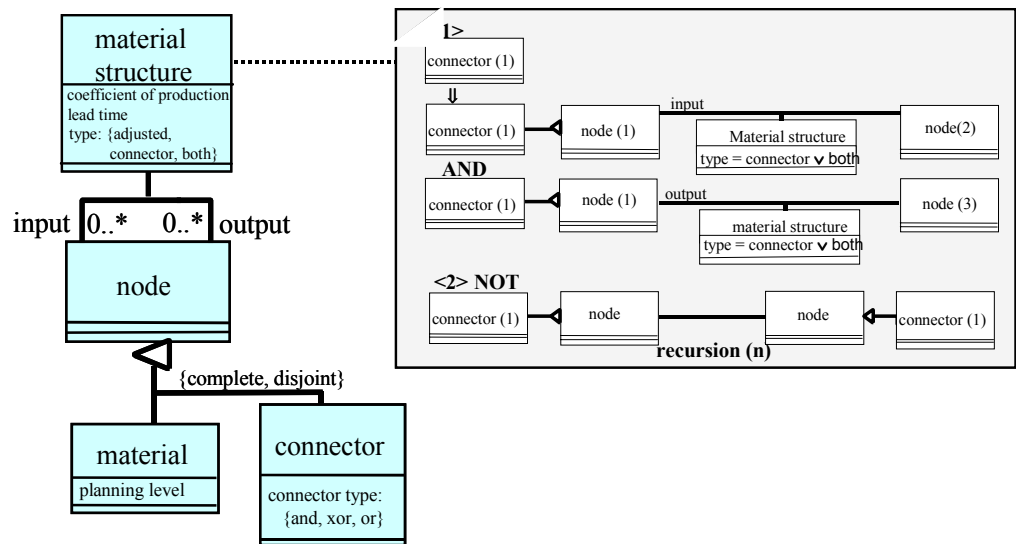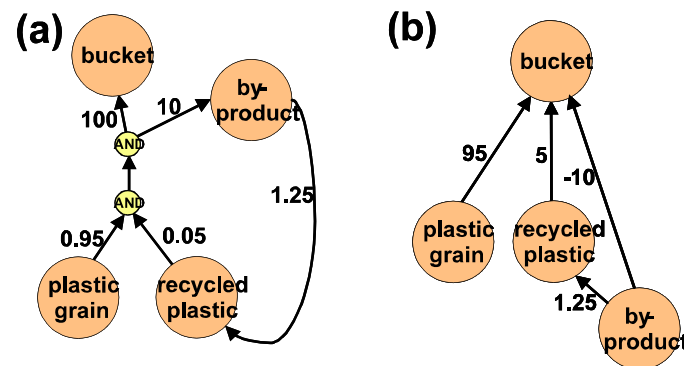
Evaluation and Limitations

With the proposed application of the approach an easy way of depicting analytic and cyclic production is provided. However, there are some limitations which restrict the scope of application domain. Following restrictions have to be considered (Loos 97):

- The adjusted gozintographs can be used for some ERP applications, in particular MRP. Other ERP applications have to use the full semantic of the connector-coded graphs.
- The algorithm for material requirements planning has to be slightly modified to process negative coefficients of production. During MRP negative requirements of input materials (e.g. M2 in Figure 5b) have to be interpreted as expected inventory additions for those materials.

- The elimination of analytic structures can only be applied if there is one single main product. All other output materials have to be by-products. Since these by-products are described as negative input materials, planning of their primary requirements is restricted (Lambotte and Turek 1991, Henson 1990).
- With the elimination of the cycle-causing edge a CP_{gross} is determined. However, the quantity of the input material (e.g. M4 in Figure 5b) computed with the CP_{gross} is a accumulation of requirements of the cycle and thus includes requirements from different planning periods. Only the quantity calculated with CP_{net} is proper concerning planning periods. The requirements covered by the quantity difference of CP_{net} and CP_{gross} tends to be required more in the future depending on the lead time, i.e. some quantities lean to be produced to early. The non-conformance increases with the quota of the material reflux in the cycle.

The proposed approach can be used to describe analytic and cyclic production in many industries like industries for mechanical engineering, plastic-processing, wood-processing, and even specialty chemicals. It contains precious solutions to handle by-products and cyclic production with common gozintograph structures in the material requirements planning. Furthermore it supports appropriated data structures and far-sighted limitations for ERP applications. The mentioned limitations prime the focus of this approach in domains where co-production and cyclic productions occur and are not the main focus of the planning activities. The solutions quality of the obtained approach is shown in the following part by a case from the plastic-processing industries.

Assuming a production with plastic injection moulding where plastic buckets are produced. To produce one bucket 100 grams of plastic is required. As raw material 95 grams of purchased plastic grain and 5 grams of recycled plastic grain is employed and represent the input. Each bucket weighs 90 grams. The residual 10 grams plastic of the raw material remain as by-product after burring the plastic bucket. In a second production process the by-product is milled yielding recycled plastic with a weight loss of 20 %. Since the bucket and by-product are produced mandatory simultaneously the bucket production is of analytic characteristics. Due to the recycling of the by-product it is regarded as cyclic production. The appropriated mixed analytic-synthetic-cyclic graph with connector coded representation is shown in Figure 7a. The CPs in the graph depict the above mentioned input-output-ratios assuming that the unit of quantity of bucket is "part" and the units of quantity of the other materials are "gram". In Figure 7b the

Figure 7. Case Plastic Injection Moulding: (a) Mixed Analytic-Synthetic-Cyclic Graph, (b) Adjusted Graph

same production processes are shown as an adjusted graph. The limitation of one single main product in the adjusted graph is not a real restriction since it is unlikely that primary requirements for the by-product are needed. The problem of accumulation of the requirements from different planning periods does not appear in this case since the cycle i eliminated with the NCP and no CP_{gross} has to be determined.

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