Data Article

Data, data flows, and model specifications for linking multi-level contribution margin accounting with multi-level fixed-charge problems

Michael Gutiérrez

Department of Business and Economics, Neu-Ulm University of Applied Sciences (HNU), Wileystr. 1, 89231 Neu-Ulm, Germany

A B S T R A C T

This article describes the data, data flows, and spreadsheet implementations for linking multi-level contribution margin accounting as a subsystem in cost accounting with several versions of a multi-level fixed-charge problem (MLFCP), the latter based on the optimization approach in operations research. This linkage can reveal previously hidden optimization potentials within the framework of multi-level contribution margin accounting, thus providing better information for decision making in companies and other organizations. For the data, plausible fictitious values have been assumed taking into consideration the calculation principles in cost accounting where applicable. They include resource-related data, market-related data, and data from cost accounting needed to analyze the profitability of a company's products and organizational entities in the presence of hierarchically structured fixed costs. The data are processed and analyzed by means of mathematical optimization techniques and sensitivity analysis. The linkage between multi-level contribution margin accounting and MLFCP is implemented in three spreadsheet files, including versions for deterministic optimization, stochastic optimization, and robust optimization. This paper provides specifications for compatible solver add-ins and for executing sensitivity analysis. The data and

spreadsheet implementations described in this article were used in a research article entitled "Making better decisions by applying mathematical optimization to cost accounting: An advanced approach to multi-level contribution margin accounting" [1]. The data sets and the spreadsheet implementations may be reused a) by researchers in management and cost accounting as well as in operations research and quantitative methods for verification and for further development of the linkage concept and of the underlying optimization models; b) by practitioners for gaining insight into the data requirements, methods, and benefits of the proposed linkage, thus supporting continuing education; and c) by instructors in academia who may find the data and spreadsheets valuable for classroom use in advanced courses. The complete spreadsheet implementations in the form of three ready-to-use Excel files (deterministic, stochastic, and robust version) are available for download at Mendeley Data. They may serve as customizable templates for various use cases in research, practice, and education.

Specifications Table

Subject	Business, Management and Accounting (General)
Specific subject area	The interface between • Cost Accounting • Operations Research / Mathematical Optimization • Spreadsheet Modeling
Type of data	Spreadsheets Figures
How data were acquired	For the data, plausible fictitious values have been assumed. Data were processed using the following software: • Microsoft Excel 2016 • Solver included in Excel 2016 (for further information, see https://support.microsoft.com and https://www.solver.com/excel-solver-online-help (accessed 22 February 2021)) • OpenSolver Version 2.9.0 (for further information, see Mason [2] and https://opensolver.org (accessed 22 February 2021)) • SolverTable 2016 (for further information, see Albright and Winston [3], pp. 87–94, and https://kelley.iu.edu/albrightbooks/Free_downloads.htm (accessed 22 February 2021)) • Analytic Solver Version 2020 by Frontline Systems Inc. (for further information, see https://www.solver.com (accessed 22 February 2021)) Hardware used: Computer (Laptop) with Intel Core i7 Processor, 16 GB RAM.
Data format	Raw Analyzed
Parameters for data collection	The data were generated taking into consideration the information needs which facilitate analysis of the profitability of a companyś products and organizational entities in the presence of hierarchically structured fixed costs. This includes resource-related data, market-related data, and data from cost accounting.

Description of data collection	Input data in the form of parameter values for an optimization model were arbitrarily chosen within plausible ranges. The calculation principles in cost accounting were considered where applicable. In a preliminary phase, a number of data sets were generated in this way. Two data sets showing different initial pictures of profitability were finally selected in order to consider different starting points for further in-depth analysis and to exemplarily demonstrate a wider range of possible effects. In the remainder of this paper, these two data sets are referred to as data set 1 and 2. A mathematical optimization model was formulated and implemented in deterministic, stochastic, and robust optimization versions. Output data were generated by applying appropriate solution methods to the model versions using suitable software. The impact of varying parameter values was tested via sensitivity analyses. Finally, the stochastic and robust versions capture the impact of uncertainty by assuming probability distributions for several parameters.
Data source location	Neu-Ulm University of Applied Sciences (HNU), Wileystr. 1, 89231 Neu-Ulm, Germany
Data accessibility	Data, overviews of data flows, and spreadsheet implementations associated with this article are available for download at: Repository name: Mendeley Data Data identification number: DOI: 10.17632/s6pswx23yx Direct URL to data: https://doi.org/10.17632/s6pswx23yx
Related research article	Michael Gutiérrez Making better decisions by applying mathematical optimization to cost accounting: An advanced approach to multi-level contribution margin accounting. Heliyon, Volume 7, Issue 2, 2021. DOI: 10.1016/j.heliyon.2021.e06096 URL: https://doi.org/10.1016/j.heliyon.2021.e06096

Value of the Data

- The data sets serve to demonstrate the benefits achievable by applying the operations research approach to cost accounting. Processing the data by means of mathematical optimization techniques can reveal previously hidden optimization potentials and unexpected effects within the framework of multi-level contribution margin accounting.
- The data sets and the spreadsheet implementations may be reused by researchers in management and cost accounting as well as in operations research and business analytics for verification and for further development of the linkage concept and of the underlying optimization models.
- The comprehensive description of the data and spreadsheet implementations in this article provides an accessible approach to the mathematically oriented concept for a broader audience. For instance, practitioners in management and cost accounting can gain insight into the data requirements, methods, and benefits of the proposed linkage. In this way, the material provided and its detailed description in this article can support continuing education.
- The material provided addresses several areas in optimization and cost accounting. Instructors in academia may find the data and spreadsheets valuable for classroom use in advanced courses, allowing students to experience the value of optimization and to perform their own analyses. Regarding the spreadsheet approach, Hillier and Hillier [4], p. viii, state: "Both business students and managers now live with spreadsheets, so they provide a comfortable and enjoyable learning environment."
- The complete spreadsheet implementations provided in the form of three ready-to-use Excel files may serve as customizable templates, potentially promoting the use of the proposed linkage concept in research, practice, and education.

1. Data Description

1.1. Preliminary remarks

1.1.1. Contents of the present article and the related research article

The present article describes how data were generated and processed within spreadsheets for linking multi-level contribution margin accounting with several versions of a multi-level fixed-charge problem (MLFCP).

The linkage is aimed at providing better information for decision making. The conceptual framework for this linkage and the mathematical formulation of the underlying MLFCP, accompanied by explanation, classification, and extensive discussion of the results, are contained in the related research article.

1.1.2. Required software and further information

The data are provided for download within three Excel files (deterministic, stochastic, and robust versions) deposited at Mendeley Data. The workbook "MLFCP deterministic.xlsx" works with the Solver included in Excel or any other compatible solver add-in, e.g., OpenSolver or the Frontline Systems Inc. Analytic Solver. Using the workbooks "MLFCP stochastic.xlsx" and "MLFCP robust.xlsx" requires the Frontline Systems Inc. Analytic Solver.

For further information on the software mentioned and used in this article, see the Section "How data were acquired" in the above Specifications Table.

1.1.3. Structure of the data description

In the following, I start with the data for the deterministic model version and then address the stochastic and robust versions only with respect to the additional data. Two fictitious data sets are considered which are contained in each of the three Excel files. Unless otherwise noted, I describe data set 1 and explicitly refer to data set 2 only where it differs from data set 1.

1.2. Data for the deterministic optimization model (Excel file: "MLFCP deterministic.xlsx")

1.2.1. Worksheet "Resource-Related Data"

In the present case study, a fictitious company (the Greedy&Grabby Corporation[1]) producing twelve products is considered. The resource-related data comprise the resource requirements per product unit and the available quantities of the resources.

1.2.2. Worksheet "Product Cost Accounting"

1.2.2.1. Conceptual basis. I assume plausible data in accordance with cost accounting principles. The conceptual basis for these data is the so-called *Grenzplankostenrechnung* (GPK).[2] Translated from German, it roughly means "flexible margin costing" (Friedl et al. [5], p. 56) or "marginal costing" (Sharman [7], p. 32). According to Friedl et al. [5], p. 56, GPK has become "… arguably the most important cost accounting system for industrial firms in German-speaking countries." Kajüter and Schröder [8], p. 17, state that "… there is now also an influence of GPK on US cost accounting."

1.2.2.2. Calculating the variable costs in product cost accounting. Referring to the principles of GPK, the variable costs of the products in the case study include direct costs (direct material

---

[1] Since the case study and the company in this paper are fictitious, they have no connection to any real companies. Any similarities with real companies are purely coincidental and not intended.

[2] GPK was originally developed by Wolfgang Kilger, a cost accounting researcher, and Hans-Georg Plaut, a practitioner (Friedl et al. [5], p. 56; Friedl et al. [6], p. 39).

and direct labor costs) as well as variable indirect costs (variable indirect material, manufacturing, and sales costs). If I do not explicitly refer to a specific worksheet in the following description, the cells or cell ranges mentioned refer to the worksheet "Product Cost Accounting". If other worksheets are addressed, they are mentioned explicitly.

Calculating the direct costs. The calculation of the direct material costs in rows 5 to 10 is based on the resource requirements per product unit from the worksheet "Resource-Related Data" (cell range D5:O9) and the related costs per unit of resource consumption in the cell range B5:B10. Since material A represents a sunk cost, its cost per unit of resource consumption is recorded as zero in cell B5. There is an additional material F in row 10, which is not subject to limited availability and therefore not listed in the constraint-related worksheet "Resource-Related Data". The required quantities of material F per product unit are displayed in row 33. All direct material costs are added together in row 11.

The calculation of the direct labor costs in rows 13 to 18 is based on the processing times from the worksheet "Resource-Related Data" (cell range D12:O17) and the related hourly labor costs in the cell range B13:B18. Without loss of generality, I assume relatively low hourly labor costs for convenience. In fact, these data could roughly apply to a "low-wage economy". All direct labor costs are added together in row 19.

Calculating the variable indirect costs. Variable indirect costs are assigned to the products by means of allocation rates in the form of percentages, machine hour rates and other rates, which are imported from the worksheet "Cost Center Accounting" (row 5). Since each of the two divisions maintains its own production facilities, the allocation rates differ between divisions D1 and D2.

The calculation of the variable indirect material costs in row 12 is based on the sum of the direct material costs in row 11 (which serves as an allocation base) and allocation rates in the form of percentages (cells B5 and H5 in the worksheet "Cost Center Accounting").

The calculation of the variable indirect costs for machining, pre-assembly, assembly, and finishing in rows 20 to 23 is based on the processing times from the worksheet "Resource-Related Data" (cell range D10:O17) and on the related allocation rates, again imported form the worksheet "Cost Center Accounting" (here cell ranges C5:F5 and I5:L5). Summing up the types of variable indirect costs mentioned yields the (total) variable indirect costs of manufacturing as reported in row 24.

The (total) variable production costs in row 25 are obtained by adding together the direct material costs (row 11), variable indirect material costs (row 12), direct labor costs (row 19), and variable indirect manufacturing costs (row 24).

Finally, the variable indirect sales costs are calculated in row 26 on the basis of the (total) variable production costs in row 25 (which serve as an allocation base) and allocation rates in the form of percentages (cells G5 and M5 in the worksheet "Cost Center Accounting").

Total variable costs. The total variable costs per unit – including all direct and variable indirect costs – are obtained in row 27 by adding together the (total) variable production costs in row 25 and variable indirect sales costs in row 26.

1.2.3. Worksheet "Cost Center Accounting"
1.2.3.1. Allocation rates.
The worksheet "Cost Center Accounting" contains the allocation rates for allocating variable indirect costs to the products in row 5.

1.2.3.2. Fixed costs.
Rows 9 and 10 store the fixed costs of the reference objects at different levels of the hierarchy for fixed cost allocation (products, product groups, divisions, company). The fixed costs used in data set 2 differ from those considered in data set 1 with respect to product group G5 and division D2. The data set chosen by the user is displayed in row 12 (this choice can be made in cell AK2 in the worksheet "MLFCP").

1.2.4. Worksheet "Market-Related Data"
1.2.4.1. Selling prices.
The worksheet "Market-Related Data" contains the selling prices of the products in the rows 4 to 5. Most selling prices used in data set 2 differ from those consid-

ered in data set 1. The data set chosen by the user is displayed in row 7 (again, this choice can be made in cell AK2 in the worksheet "MLFCP").

1.2.4.2. Upper & lower bounds on sales volumes, minimum number of products. Furthermore, for each product, upper bounds on sales volumes hold due to saturation of the markets (row 9). Lower bounds on sales volumes (row 10) and a minimum number of products to be produced (cell A13) may be considered as well.

1.2.5. Worksheet "Initial Solution"

This worksheet reports the initial solution for the production (i.e., sales) volumes and binary variables, i.e., the solution before applying mathematical optimization. This solution is the basis for the initial multi-level contribution margin calculation as shown in Figure 6 of the related research article.

1.3. Data for the stochastic optimization model (Excel file: "MLFCP stochastic.xlsx")

1.3.1. Basis

The stochastic version is based on the deterministic version. Therefore, only the additional data are described. The stochastic version assumes uncertain selling prices of the products and uncertain purchase prices of the materials.

1.3.2. Worksheet "Market-Related Data"

I assume triangular distributions for the selling prices with three different specifications: symmetric, left-skewed, and right-skewed distribution. These specifications are given in the cell range O8:R13. The assumed rank correlations between the selling prices are contained in the correlation matrix in the cell range B21:M32. Defining and processing of the uncertain selling prices according to the assumed probability distributions and correlation matrix are described in detail in Section 2.4.

It should be noted that in comparison to the deterministic version, the upper and lower bounds on sales volumes as well as the minimum number of products have been shifted down to rows 36 to 40.

1.3.3. Worksheet "Product Cost Accounting"

I also assume triangular distributions for the purchase prices of the materials with three different specifications: symmetric, left-skewed, and right-skewed distribution. These specifications are given in the cell range P13:U16. The assumed rank correlations between the purchase prices are contained in the correlation matrix in the cell range X6:AB10. Defining and processing of the uncertain purchase prices according to the assumed probability distributions and correlation matrix are described in detail in Section 2.4.

1.4. Data for the robust optimization model (Excel file: "MLFCP robust.xlsx")

1.4.1. Basis

The robust version is based on the stochastic version. Therefore, only the additional data are described. In the robust version, not only the selling prices and purchase prices, but also some of the processing times are considered as uncertain.

1.4.2. Worksheet "Resource-Related Data"

I assume right-skewed triangular distributions for the processing times in the pre-assembly of division D1. The specifications are given in the cell range K23:K25. Definition and treatment of the uncertain processing times according to the assumed probability distribution are described in detail in Section 2.5.

2. Experimental Design, Materials and Methods

Based on the data modules described in Section 1, I now show how these data are processed within the spreadsheet implementations, and start with an overview of the data flows between the various data modules.

2.1. Big picture – overview of data flows

Putting together all the data modules as described in Section 1 and adding the implementation of multi-level contribution margin accounting and of the MLFCP in Excel, an overview of the data flows between the various worksheets is obtained. This overview is available for download at Mendeley Data in three versions which correspond to the deterministic, stochastic, and robust versions of the MLFCP (these are oversize graphics; please scale up appropriately to see the details). The worksheets shown in the overviews correspond to the worksheets in the related Excel files. In this way, the overviews provide detailed spreadsheet-based concretions of my "linking framework" as shown in Figure 4 of the related research article. In order to highlight the correspondence, a similar color scheme is used in both representations.

Selected important data flows in the deterministic version (as well as in the other two versions) of the overview can be outlined as follows: The resource requirements per product unit (see the "Resource-Related Data" in the upper left of the overview) simultaneously flow into the resource constraints of the MLFCP and into the calculation of the variable costs in product cost accounting. The variable costs calculated here flow into the objective function coefficients of the production quantities in the MLFCP and into multi-level contribution margin accounting. The optimal values of all decision variables obtained from the MLFCP – including the production (i.e., sales) quantities and the binary variables – are finally fed into multi-level contribution margin accounting. In the stochastic and robust versions of the overview, selected important data and data flows tainted with uncertainty are highlighted by red borders, lines, and arrows. Specific aspects of these versions are addressed in the subsequent sections.

The implementation of the MLFCP as sketched in the overviews is specified in the following sections with regard to its

- deterministic version (Section 2.2),
- stochastic version (Section 2.4), and
- robust version (Section 2.5)

Furthermore, specifications for sensitivity analysis are provided (Section 2.3). Finally, I briefly address the flow of the output data from the MLFCP to multi-level contribution margin accounting (Section 2.6).

2.2. Specifications for the deterministic optimization model (Excel file: "MLFCP deterministic.xlsx")

I now refer to the Excel file "MLFCP deterministic.xlsx" provided at Mendeley Data. In the worksheet "MLFCP", the structure of the MLFCP in the form of a deterministic optimization model can be outlined as follows:

2.2.1. Choosing the data set
The data set (1 or 2) can be chosen in cell AK2.

2.2.2. Decision variables
The decision variables are stored in the yellow highlighted cell range B4:AF4 (name: Decision_variables). They include the production quantities in the cell range B4:M4 (name: Produc-

tion_quantity) and the binary variables of the various reference objects for fixed cost allocation in the cell range N4:AF4 (name: Binary_variables).

2.2.3. Objective function

The objective function is contained in the green highlighted cell AG5 (name: CM_IV). It computes the total contribution margin IV (CM IV) by the Excel formula

$$= \text{SUMPRODUCT(B5:AF5, Decision\_variables)}$$

where the cell range B5:AF5 stores the objective function coefficients in the form of the contribution margins per unit of the products (B5:M5) and the fixed costs of the various reference objects (N5:AF5).

2.2.4. Constraints

In the following, the numbers in brackets refer to the numbers of the corresponding constraints of the MLFCP as formulated in the related research article.

2.2.4.1. Resource constraints. Rows 7 to 19 in the worksheet contain the resource constraints (8).

2.2.4.2. Linking constraints[3]. Rows 20 to 31 store the (equivalently reformulated) linking constraints (9), which simultaneously perform the function of sales restrictions because the upper bounds on sales volumes from the worksheet "Market-Related Data" are used as values for M_{j_1}. The linking constraints (10) are implemented in rows 32 to 38; since the structure of levels and reference objects in the case study represents an excerpt of the exemplary structure in Figure 3 of the related research article, the concrete formulations of the linking constraints (10) in rows 32 to 38 can be taken from that figure (again, equivalently reformulated in the Excel implementation). To illustrate these linking constraints, some examples are considered. Product group G1 contains the products P1 and P2; therefore, cells N32 and O32 each contain the value one and cell Z32 the value −2. Product group G2 contains the products P3, P4, and P5; therefore, cells P33, Q33, and R33 each contain the value one and cell AA33 the value −3. Division D1 contains the product groups G1, G2, and G3; therefore, cells Z37, AA37, and AB37 each contain the value one and cell AE37 the value −3.

2.2.4.3. Lower bounds on sales volumes. Possible – but not necessarily applicable – constraints regarding lower bounds on sales volumes (i.e., production quantities) and a minimum number of products to be produced are stored in rows 39 to 68; they correspond to the constraints (13) to (16) in the related research article after reformulating these as equivalent less-than-or-equal-to constraints. They can be switched on and off in cells AK39 and AK51 (1 = on, 0 = off).

2.2.4.4. Generating all constraints. The left-hand sides (LHS) of all above-mentioned constraints can be generated on the basis of the Excel formula in cell AG7, which takes the form:

$$= \text{SUMPRODUCT(B7:AF7, Decision\_variables)}$$

Here, the cell range B7:AF7 contains the coefficients in the LHS of the constraint. This formula can be copied throughout to cell AG68.

2.2.5. Model classification, compatible solvers, solver settings & options
2.2.5.1. Classification of the model. The model is an integer (linear) programming model.

---

[3] For the term linking constraints, see, e.g., Baker [9], p. 231. It should be noted, however, that the general term "linking constraints" used in the literature in connection with certain integer programming models is by no means necessarily associated with my specific "linking framework" addressed in Section 2.1. By contrast, the linking constraints in the present article and in the related research article are explicitly part of this linking framework.

2.2.5.2. Compatible solvers. Any compatible add-in for Excel providing a solver for integer programming can be used to implement and solve the model, for example:[4]

- Solver included in Excel
- OpenSolver
- Analytic Solver by Frontline Systems Inc.

2.2.5.3. Solver settings.

Objective cell: CM_IV (AG5) (Max)
Variable cells: Decision_variables (B4:AF4)
  Constraints: LHS (AG7:AG68) <= RHS (AI7:AI68)
            Binary_variables (N4:AF4) = binary

2.2.5.4. Solver options (Solver included in Excel // OpenSolver // Frontline Systems Inc. Analytic Solver). Make Unconstrained Variables Nonnegative // Make unconstrained variable cells non-negative // Assume Non-Negative: True
    Solving Method: Simplex LP // COIN-OR CBC (Linear solver) // Standard LP/Quadratic engine
    Integer Optimality (%): 0 // Branch and Bound Tolerance (%): 0 // Integer Tolerance: 0

2.2.5.5. Note on integer constraints. The solver settings in the deterministic version do include binary integer (0/1) restrictions for the binary variables but do not yet include general integer constraints regarding the production quantities because they are not necessary in all cases (they are required, for example, when lower bounds on sales volumes apply). If necessary, one can add general integer constraints in the solver settings in order to yield the exact results shown in the related research article. However, depending on the type of solver used, this can lead to an increase in the solution time. In the stochastic and robust version, the solver settings include general integer constraints regarding the production quantities.

2.2.6. Initial solution
    The worksheets "MLFCP" and "MLCMA" currently show the *initial solution* (i.e., still *without* optimization). If one wants to go back to this initial solution at any time, one can copy the initial solution contained in the worksheet "Initial Solution" (cell range B4:AF4) into the worksheet "MLFCP" (cell range B4:AF4).
    By contrast, the corresponding overview of the data flows (deterministic version) shows the optimal solution.

2.3. Specifications for sensitivity analysis

2.3.1. Basis
    The deterministic version of the optimization model as configured in Section 2.2 serves as a basis for executing sensitivity analysis. Bearing in mind that the interpretation of dual values (or shadow prices) obtained in continuous linear programming models cannot be maintained in integer programming models, which is the model class on hand here, I used the below listed Excel add-ins in order to perform sensitivity analysis.

2.3.2. SolverTable
    The SolverTable add-in[5] invokes the Solver included in Excel for automatic execution of multiple optimization runs across varying parameter values.

---

[4] For further information on the software, see the Section "How data were acquired" in the Specifications Table.
[5] For further information on the software, see the Section "How data were acquired" in the Specifications Table.

2.3.3. Analytic Solver by Frontline Systems Inc

In the Frontline Systems Inc. Analytic Solver, an optimization report based on the PsiOptParam() function automatically runs multiple optimizations for varying parameter values and shows how the results change (see Frontline Systems [10], p. 304; more reports are available). To test the robustness of the optimal decisions with respect to percentage changes in the fixed costs, I specified the PsiOptParam() function, for example, as follows:

$$= \text{PsiOptParam}(-100, 400)$$

where -100 is the lower limit and 400 the upper limit for the parameter to be varied. (An optional base case value used for the cell when not running multiple optimizations can be added). In the present analysis, I interpret the lower limit as maximum percentage decrease (i.e., -100%) and the upper limit as maximum percentage increase (i.e., 400%); for the latter, different values were tested, ranging from 200 (i.e., 200%) up to 700 (i.e., 700%). The cell containing the PsiOptParam() function was then divided by 100, the value one was added, and the resulting factor finally multiplied with the fixed cost element(s) under consideration. Next, Analytic Solver generated an optimization report in the form of a parameter analysis. In the settings for the multiple optimizations report, all decision variables and the objective cell (CM_IV) were selected as result cells and the cell containing the PsiOptParam() function as a parameter cell. The desired increment for variation can be specified in the field "Major Axis Points"; regarding the above exemplary specification of the PsiOptParam() function covering the range from -100 to 400, an input value of 501 for this field corresponds with increments of one percentage point in my implementation. Analytic Solver will automatically now run 501 optimizations.

Proceeding with Analytic Solver, a sensitivity analysis based on the PsiSenParam() function does not run a new optimization but shows how a formula-dependent cell changes when parameters are varied (see Frontline Systems [10], p. 304). To test the impact of percentage changes in the selling prices on the objective function value while keeping the values of the decision variables, I specified the PsiSenParam() function, for example, as follows:

$$= \text{PsiSenParam}(-30, -10)$$

where -30 is the lower limit and -10 the upper limit for the parameter to be varied. (Again, an optional base case value used for the cell when not running a sensitivity analysis can be added). In this case, I interpret the lower limit as maximum percentage decrease (i.e., -30%) and the upper limit as minimum percentage decrease (i.e., -10%). The cell containing the PsiSenParam() function was then divided by 100, the value one was added, and the resulting factor finally multiplied with the selling price under consideration. Next, Analytic Solver generated a sensitivity report in the form of a parameter analysis. In the sensitivity report settings, the objective cell (CM_IV) was selected as a result cell and the cell containing the PsiSenParam() function as a parameter cell. Again, the desired increment for variation can be specified in the field "Major Axis Points". Here, I considered increments of 10 percentage points, which in the present case corresponds with an input value of three in this field.

2.3.4. OpenSolver

For additional examination, I also used OpenSolver to perform several optimization runs with respect to a limited number of different parameter values.

2.4. Specifications for the stochastic optimization model (Excel file: "MLFCP stochastic.xlsx")

2.4.1. Basis

The basic structure of the stochastic optimization model corresponds with the structure of the deterministic version described in Section 2.2; therefore, I now only focus on the specific implementation aspects in the stochastic version (for an overview and detailed methods of stochastic optimization, see, e.g., Marti [11]; Kall and Mayer [12]). Reference here is to the Excel file "MLFCP stochastic.xlsx" and to the stochastic version of the overview provided at Mendeley Data.

2.4.2. Software

Based on the deterministic optimization model, the stochastic version was implemented and solved using the Frontline Systems Inc. Analytic Solver.

2.4.3. Worksheet "Market-Related Data"

2.4.3.1. Probability distributions. The assumed triangular distributions for the selling prices are contained in the cell range O8:R13, where specifications for a symmetric, left-skewed and right-skewed distribution – which in this paper are associated with normal, optimistic, and pessimistic expectations, respectively – are reported. These specifications are given in the form of factors in the cell range P11:R13, which are to be applied to the originally deterministic values of the selling prices in the cell range B7:M7. The type of expectations can be chosen in cell R15; as a result, the related factors for the lower bound a, mode c, and upper bound b are adopted in the cell range N11:N13 and finally applied to the selling prices in the cell range B11:M13.

2.4.3.2. Rank correlations. As already mentioned, the assumed rank correlations between the selling prices of each pair of products are contained in the cell range B21:M32.

2.4.3.3. Implementation. For the uncertain selling price of product P3, for example, the corresponding random values in cell D15 of the worksheet are generated by the function

$$= \mathrm{PsiTriangular}(\mathrm{D11}, \mathrm{D12}, \mathrm{D13}, \mathrm{PsiCorrMatrix}(\$\mathrm{B}\$21{:}\$\mathrm{M}\$32, 3, \text{"Selling Prices"}))$$

where the cells D11, D12, and D13 contain the lower bound a, mode c and upper bound b as a result of applying the factors contained in the cell range N11:N13 to the selling price in cell D7; the cell range $B$21:$M$32 contains the correlation matrix for the selling prices; the selling price of product P3 is in the third position, i.e., the third uncertain parameter covered by the correlation matrix; finally, "Selling Prices" is a user-defined name for the correlation matrix.

The random values for all selling prices as determined in the cell range B15:M15 finally flow into the objective function coefficients in the cell range B5:M5 in the worksheet "MLFCP".

2.4.4. Worksheet "Product Cost Accounting"

2.4.4.1. Probability distributions. The assumed triangular distributions for the purchase prices are contained in the cell range P13:U16, where specifications for a symmetric, right-skewed, and left-skewed distribution – which in this paper are associated with normal, optimistic, and pessimistic expectations, respectively – are reported. Again, these specifications are given in the form of factors in the cell range S14:U16, which are to be applied to the originally deterministic values of the purchase prices in the cell range R6:R10. The type of expectations can be chosen in cell S18; as a result, the related factors for the lower bound a, mode c, and upper bound b are adopted in the cell range S11:U11 and finally applied to the purchase prices in the cell range S6:U10 (not applicable to material A, because this material represents a sunk cost in this case study).

2.4.4.2. Rank correlations. As already mentioned, the assumed rank correlations between the purchase prices of each pair of materials are contained in the cell range X6:AB10.

2.4.4.3. Implementation. For the uncertain purchase price of material C, for example, the corresponding random values in cell B7 of the worksheet are generated by the function

$$= \mathrm{PsiTriangular}(\mathrm{S7}, \mathrm{T7}, \mathrm{U7}, \ \mathrm{PsiCorrMatrix}(\$\mathrm{X}\$6{:}\$\mathrm{AB}\$10, 2, \text{"Purchase Prices"}))$$

where the cells S7, T7, and U7 contain the lower bound a, mode c and upper bound b as a result of applying the factors contained in the cell range S11:U11 to the purchase price in cell R7; the cell range $X$6:$AB$10 contains the correlation matrix for the purchase prices; the purchase price of material C is in the second position, i.e., the second uncertain parameter covered by the correlation matrix; finally, "Purchase Prices" is a user-defined name for the correlation matrix.

The random values for all purchase prices as determined in the cell range B6:B10 flow into the product cost calculation in the cell range C6:N10; thus, they flow into the variable costs in the cell range C27:N27 which for their part finally flow into the objective function coefficients in the cell range B5:M5 in the worksheet "MLFCP".

2.4.5. Worksheet "MLFCP"

The new objective cell AI5 (named Expected_value_CM_IV), which was added to the Excel worksheet, now contains the function

$$= \text{PsiMean(CM\_IV)}$$

where the cell named CM_IV (AG5) is the old objective cell still computing the total contribution margin IV. Hence, the mean (expected) value of total contribution margin IV is now maximized. The related standard deviation in cell AJ5 is calculated by the function

$$= \text{PsiStdDev(CM\_IV)}$$

2.4.6. Solving the model

Referring to the prices on the selling and purchasing side, I consider all nine possible combinations of the symmetric, right-skewed and left-skewed distributions, resulting in nine scenarios for the associated expectations. For each scenario, the related – originally stochastic – optimization model is transferred by Analytic Solver into its deterministic equivalent linear program (for further information, see Frontline Systems [10]). Hence, all models can be solved using the Standard LP/Quadratic Engine in Analytic Solver. The results shown in the overview (stochastic version) are based on the combination of normal expectations on the selling and purchasing side. Due to a certain variation in the outcome obtained by Monte Carlo Simulation, the expected value of CM IV and the related standard deviation shown in the overview slightly differ from the corresponding values reported in Table 9 of the related research article.

2.5. Specifications for the robust optimization model (Excel file: "MLFCP robust.xlsx")

2.5.1. Basis

All the specifications in the stochastic version regarding the uncertain selling prices and purchase prices as well as the objective function as described in Section 2.4 are retained in the robust version. Therefore, I now only focus on the specific implementation aspects in the robust version. Reference here is to the Excel file "MLFCP robust.xlsx" and to the robust version of the overview provided at Mendeley Data.

2.5.2. Software

Based on the stochastic optimization model, the robust version was implemented and solved using the Frontline Systems Inc. Analytic Solver.

2.5.3. Worksheet "Resource-Related Data"

2.5.3.1. *Probability distributions.* The assumed triangular distributions for the processing times in the pre-assembly of division D1 are contained in the cell range B22:K25. Again, these specifications are given in the form of factors in the cell range K23:K25, which are to be applied to the originally deterministic values of the processing times in the cell range D20:J20. In so doing, the lower bounds a, modes c, and upper bounds b are obtained in the cell range D23:J25.

2.5.3.2. *Rank correlations.* Correlations are not considered here.

2.5.3.3. Implementation. For the uncertain processing time of product P1, for example, the corresponding random values in cell D27 of the worksheet are generated by the function

$$= \text{PsiTriangular}(D23, D24, D25)$$

where the cells D23, D24, and D25 contain the lower bound *a*, mode *c*, and upper bound *b* as a result of applying the factors contained in the cell range K23:K25 to the processing time in cell D20.

The random values for the processing times as determined in the cell range D27:J27 are adopted in the cell range D12:J12. From here, they flow into the corresponding constraint for the pre-assembly in division D1 in the worksheet "MLFCP", where they serve as constraint coefficients in the cell range B14:H14.

2.5.4. Worksheet "MLFCP"

2.5.4.1. Chance constraint. I now formulate the pre-assembly constraint for division D1 in row 14 as a chance constraint that will be satisfied in most (but not necessarily all) cases across the realizations of the uncertain factors. This corresponds with a chance constraint of the type "Value at Risk" (VaR). (for an overview and applications of various types of chance constraints, see Frontline Systems [10], pp. 168–173 and 536–540; Birge and Louveaux [13], pp. 34, 47, 84–86, 124–134, 146–148; Kall and Mayer [12], pp. 88–91). In the "Add constraint" box in Analytic Solver, this type of chance constraint is specified by choosing the option VaR and inserting the desired percentile into the field "Chance". In the present analysis, the chance constraint was defined alternatively for the 99% and 95% percentile.

2.5.4.2. Actual probability for satisfying the chance constraint. The actual probability of satisfying the chance constraint – estimated by the corresponding relative frequency across all realizations of the uncertainties – can be tracked using the PsiTarget() function in cell AP14 as follows:

$$= \text{PsiTarget}(AN14, 0)$$

where cell AN14 computes the difference between the left-hand side (LHS) and right-hand side (RHS) of the chance constraint (i.e., AG14 (LHS) – AI14 (RHS)). The PsiTarget() function determines the proportion of values – in the present case of cell AN14 – less than or equal to a target value, here 0 (for the PsiTarget() function, see Frontline Systems [10], p. 490). Thus, the PsiTarget() function as specified above checks the condition LHS–RHS $\leq$ 0, which – if true – means that the constraint is not violated. Hence, the relative frequency of satisfying the constraint is obtained.

2.5.4.3. Other constraints. Since row 14 now contains a chance constraint as described above, the other constraints were split up into two sets, the first set containing the constraints in the rows 7 to 13 and the second set containing the constraints in the rows 15 to 68.

2.5.5. Solving the model

Analytic Solver automatically transforms the stochastic optimization model including the above-mentioned chance constraint into its robust counterpart in the form of a deterministic linear program with more variables and constraints; hence, the model can be solved using the Standard LP/Quadratic Engine in Analytic Solver. Solving the transformed model yields an approximate solution to the originally stochastic problem. (Frontline Systems [10], p. 170; on the methods of robust optimization, see Ben-Tal et al. [14]). The results shown in the overview (robust version) are based on the 99% percentile for the chance constraint and on the combination of normal expectations on the selling and purchasing side. Once again, the expected value of CM IV shown in the overview slightly differs from the corresponding value reported in Table 10 of the related research article.

2.6. Transferring the output of the MLFCP to multi-level contribution margin accounting

As illustrated in the overviews of the data flows introduced in Section 2.1, the values of the decision variables of the MLFCP are finally fed into multi-level contribution margin accounting (worksheet "MLCMA" in all versions). While this data flow is primarily of interest for the *optimal* values of the decision variables, *any* solution from the MLFCP is transferred to multi-level contribution margin accounting. It should be noted that in the stochastic and robust versions, the contribution margins I in row 8 of the worksheet "MLCMA" are calculated by means of PsiMean() functions.

The interpretation of the linkage concept and the conclusions are extensively discussed in the related research article.

Note on registered names, trademarks, etc

Registered names, trademarks, etc. mentioned in this paper, even when not specifically marked as such, are not to be considered unprotected by law. They are the property of their respective owners. The use of any trademark in this paper does not vest in the author any trademark ownership rights in such trademarks, nor does the use of such trademarks imply any affiliation with or endorsement of this paper by such owners.

CRediT Author Statement

Michael Gutiérrez: Conceptualization, Methodology, Validation, Formal analysis and implementation in spreadsheets, Investigation, Data curation, Writing - Original draft, Writing - Reviewing and Editing, Visualization.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

Data Availability

Spreadsheet Implementations for Linking Multi-Level Contribution Margin Accounting with Multi-Level Fixed-Charge Problems (Original data) (Mendeley Data).

References

[1] M. Gutiérrez, Making better decisions by applying mathematical optimization to cost accounting: An advanced approach to multi-level contribution margin accounting, Heliyon 7 (2) (2021).
[2] A.J. Mason, OpenSolver – an open source add-in to solve linear and integer progammes in excel, in: D. Klatte, H.-J. Lüthi, K. Schmedders (Eds.), Operations Research Proceedings 2011, Springer, Berlin, Heidelberg, 2012, pp. 401–406, doi:10.1007/978-3-642-29210-1_64.
[3] S.C. Albright, W.L. Winston, Management Science modeling, 4th International ed, Cengage Learning, South-Western, 2012.

[4] F.S. Hillier, M.S. Hillier, Introduction to Management Science. A Modeling and Case Studies Approach with Spread-sheets, 5th International ed, McGraw-Hill, New York NY, 2014.

[5] G. Friedl, H.-U. Küpper, B. Pedell, Relevance added: combining ABC with German cost accounting, Strategic Finance (June 2005) 56–61.

[6] G. Friedl, C. Hammer, B. Pedell, H.-U. Küpper, How do German companies run their cost accounting systems? Manag. Account. Q. 10 (2) (2009) 38–52.

[7] P.A. Sharman, Bring on German cost accounting, Strategic Finance (December 2003) 30–38.

[8] P. Kajüter, M. Schröder, Cost accounting systems in Germany and the USA: a cross-national comparison and em-pirical evidence, in: M. Buttkus, R. Eberenz (Eds.), Performance Management in Retail and the Consumer Goods Industry: Best Practices and Case Studies, Springer, Cham, 2019, pp. 11–26.

[9] K.R. Baker, Optimization Modeling With Spreadsheets, 3rd ed., Wiley, Hoboken, New Jersey, 2016.

[10] Frontline SystemsAnalytic Solver Optimization Analytic Solver Simulation User Guide, Frontline Systems, Inc., Incline Village, NV, 2020. https://www.solver.com. Accessed February 22, 2021.

[11] K. Marti, Stochastic Optimization Methods. Applications in Engineering and Operations Research, Springer, Berlin, Heidelberg, 2015.

[12] P. Kall, J. Mayer, Stochastic Linear programming: models, theory, and Computation, 2nd ed., Springer, New York, 2011.

[13] J.R. Birge, F. Louveaux, Introduction to Stochastic Programming, 2nd ed., Springer, New York, NY, 2011.

[14] A. Ben-Tal, L. El Ghaoui, A. Nemirovskij, Robust Optimization, Princeton, N.J, Princeton Univ. Press, 2009.