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Bachelor of Business Administration (BBA) | Fifth Semester | UK5DSCMGT301

Operations Management

Course Code: UK5DSCMGT301 • Module 2 Notes

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Module 2: Designing Operations and Work Systems

Operations Management • Course Code: UK5DSCMGT301

Chapter 1: Product Design and Development Processes

1.1 Generation, Conceptualization, and Screening of New Product Ideas

Product design is the foundational strategic activity that defines the physical form, utility, functional performance, aesthetic appeal, material composition, and manufacturing specifications of an enterprise's commercial offerings. In modern industrial economics, product design dictates up to eighty percent of total product lifecycle costs, including raw material procurement, factory processing, packaging, logistics, warranty servicing, and end-of-life environmental disposal. A deficient product design cannot be redeemed by operational efficiency on the shop floor or aggressive marketing campaigns; early design excellence is the single greatest determinant of enterprise profitability and market success.

The structured product development journey traverses several distinct developmental phases:

- **1. Idea Generation:** Sourcing creative concepts from internal stimuli (basic scientific research, corporate R&D laboratories, customer service warranty data, and shop-floor suggestion programs) and external stimuli (competitor reverse engineering, consumer focus groups, vendor technological advancements, patent filings, and emerging regulatory requirements).
- **2. Concept Screening and Evaluation:** Filtering raw concepts using multi-criteria matrices to evaluate technical feasibility, market size, expected profit margins, capital investment requirements, regulatory compliance, and strategic alignment with organizational core competencies.
- **3. Preliminary Design and Feasibility Analysis:** Translating selected concepts into functional engineering prototypes, establishing basic material specifications, defining subsystem architectures, and performing rigorous financial break-even analyses under varying volume scenarios.
- **4. Prototype Testing and Validation:** Subjecting working prototypes to mechanical stress testing, thermal cycling, consumer usability trials, and accelerated lifecycle performance evaluation under environmental extremes.
- **5. Final Design and Production Tooling:** Generating definitive computer-aided design (CAD) blueprints, detailed engineering tolerances, bills of materials (BOM), assembly routing instructions, and specialized tooling fabrication for commercial production.

1.2 Contemporary Engineering Methodologies in Product Design

To eliminate costly redesign loops, minimize engineering change orders (ECOs), and accelerate time-to-market, leading industrial firms deploy advanced interdisciplinary design methodologies:

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1. Concurrent Engineering (Simultaneous Engineering): Traditional product development operated on a sequential "over-the-wall" model, where research scientists passed conceptual sketches to development engineers, who then tossed blueprints to manufacturing engineers, who subsequently handed production plans to marketing. This linear approach caused severe communication breakdowns, extensive engineering change orders (ECOs), and delayed product launches. *Concurrent Engineering* replaces this siloed structure with cross-functional teams (including product designers, manufacturing specialists, procurement managers, quality engineers, and marketing executives) who collaborate simultaneously from Day One. Manufacturing tooling, supply chain agreements, and service manuals are developed concurrently with product styling, dramatically reducing development lead times and engineering rework.

2. Design for Manufacturing and Assembly (DFMA): A systematic engineering discipline focused on optimizing product geometry to make components easy to manufacture and rapid to assemble:

- *Part Count Reduction:* Consolidating multiple separate components into single integrated molded parts, eliminating fasteners, screws, and assembly joints.
- *Standardization:* Utilizing universal off-the-shelf screws, bearings, and connectors across different product lines.
- *Modular Design:* Creating self-contained sub-assemblies (e.g., standard automotive powertrains or computer motherboards) that can be swapped or upgraded independently.
- *Mistake-Proofing (Poka-Yoke):* Designing mating parts with asymmetrical geometries so they can physically only be assembled in the correct orientation.

3. Quality Function Deployment (QFD) and the House of Quality: Invented at Mitsubishi's Kobe shipyards and refined by Toyota, QFD is a structured graphic planning methodology that systematically translates subjective consumer desires (the "Voice of the Customer" or WHATs) into objective, measurable engineering specifications (the "Voice of the Engineer" or HOWs). The central planning matrix, termed the *House of Quality*, correlates customer requirements with technical parameters, benchmarks rival products, and identifies engineering trade-offs.

QFD Component	Structural Elements	Managerial Utility
Customer Requirements (WHATs)	Structured hierarchy of customer needs, weighted by importance ratings (1 to 5).	Prevents engineers from over-designing features customers do not value.
Technical Characteristics (HOWs)	Measurable engineering parameters (e.g., tensile strength, weight in grams, decibels).	Translates ambiguous customer language into actionable manufacturing tolerances.
Relationship Matrix	Intersections scored as Strong (9), Moderate (3), or Weak (1) correlation.	Identifies which technical parameters exert maximum impact on customer satisfaction.

QFD Component	Structural Elements	Managerial Utility
Correlation Roof	Triangular matrix mapping trade-offs between different engineering HOWs (+ or -).	Highlights physical conflicts (e.g., increasing structural strength increases vehicle weight).

1.3 Value Engineering and Value Analysis (VE/VA)

Pioneered by Lawrence D. Miles at General Electric during World War II, **Value Engineering (VE)** and **Value Analysis (VA)** represent systematic, organized approaches for evaluating the functional design of product components to achieve essential functions at the lowest lifecycle cost without sacrificing quality, reliability, performance, or aesthetic appeal. While *Value Engineering* is applied proactively during early product design stages before commercial tooling is fabricated, *Value Analysis* is applied retroactively to existing, manufactured products to identify cost-saving modifications and material substitutions.

The concept of Value is defined mathematically as the ratio of Function to Cost:

```
Value = Function / Cost
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Where: Function is the specific utility, mechanical action, or aesthetic purpose the component performs, and Cost represents total lifecycle manufacturing and material expenditure.

Value can be increased in four distinct operational ways: (1) Increasing functional performance while holding costs constant; (2) Maintaining existing functional performance while reducing manufacturing costs; (3) Increasing functional performance while simultaneously reducing costs (the ideal outcome); or (4) Slightly reducing non-critical secondary functions while achieving massive percentage reductions in cost.

The Function Analysis System Technique (FAST): VE teams analyze components by decomposing their utility into verb-noun pairings classified into *Basic Functions* (the primary, indispensable reason the item exists, such as "interrupt current" for a circuit breaker) and *Secondary Functions* (supporting or aesthetic roles, such as "indicate status"). Unnecessary costs usually hide in over-engineered secondary functions.

1.4 Taguchi's Quality Loss Function and Robust Design

Japanese engineer Genichi Taguchi revolutionized product design by establishing the philosophy of **Robust Design**. Taguchi argued that traditional engineering tolerances (the "goal-post" mentality, where any dimension inside specification limits is considered completely acceptable and any dimension outside is totally rejected) failed to capture economic reality. According to Taguchi, any deviation from the nominal target specification imposes a hidden societal and customer cost that increases quadratically:

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L(y) = k × (y - m)^2
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> Where: L(y) is the economic quality loss, y is the actual measured dimension, m is the nominal target specification, and k is a cost coefficient.

Taguchi's *Parameter Design* methodology optimizes design parameters so that product performance remains virtually immune ("robust") to environmental variations (ambient temperature, humidity, vibration) and component wear without requiring expensive, ultra-tight manufacturing tolerances.

Chapter 2: Process Design, Selection, and Analysis

2.1 Classification of Operational Process Types

Process Design determines how physical resources, human labour, and machinery are systematically organized to execute the transformation process. Process choice represents a fundamental long-term commitment that directly shapes unit production costs, manufacturing flexibility, and workforce skill requirements. The classical *Product-Process Matrix*, developed by Robert Hayes and Steven Wheelwright, categorizes operating processes into five distinct archetypes along the continuum of volume and product variety:

Process Type	Product Characteristics	Operational Configuration	Managerial Implications
Project	One-off, highly customized, complex, large-scale (e.g., dam construction, commercial shipbuilding, software development).	Fixed-position layout where resources, labour, and heavy machinery move to the stationary project site. Highly specialized tasks.	Long production lead times, unique sequence of operations, critical reliance on PERT/CPM scheduling, high unit cost.
Job Shop	Low volume, wide product variety, customized orders (e.g., custom machine fabrication, precision printing, tool and die making).	Functional/Process layout grouping identical machinery into specialized departments. General-purpose machinery and high craft skills.	High work-in-process (WIP) inventories, complex routing and job scheduling, high variable costs, high operational flexibility.
Batch Production	Moderate volume, medium variety, recurring product families (e.g., pharmaceuticals,	Equipment set up to process a specific batch of identical items, followed by cleaning and machine changeovers for the next batch.	Capacity losses during machine setups, delicate balance of economic batch sizing, moderate unit costs and inventory holdings.

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Process Type	Product Characteristics	Operational Configuration	Managerial Implications
	commercial bakeries, apparel manufacturing).		
Mass Production (Assembly Line)	High volume, low variety, standardized discrete units (e.g., passenger car assembly, smartphone manufacturing, domestic appliances).	Product layout with dedicated workstations arranged in a strict linear sequence matching the product assembly sequence. Specialized machinery.	Low skilled labour requirements, highly balanced paced conveyor lines, very low variable cost per unit, high capital investment.
Continuous Flow	Extremely high volume, highly standardized non-discrete commodity fluids or bulk goods (e.g., petroleum refining, chemical processing, sugar mills).	Highly automated, 24/7 continuous thermodynamic, chemical, or mechanical flow. Dedicated pipeline and reactor infrastructures.	Extreme capital intensity, minimal direct human labour, catastrophic economic loss if shut down unexpectedly, absolute inflexibility.

2.2 Process Mapping and Flow Chart Analysis

To eliminate operational inefficiencies, eliminate non-value-adding delays, and optimize process flow, operations analysts utilize standardized **Process Flow Charts** and **Value Stream Maps**. The American Society of Mechanical Engineers (ASME) established five universal symbolic notations to document every operational touchpoint:

- **Operation (Circle ◯):** Represents a value-adding conversion step where the physical, chemical, or informational properties of an item are intentionally altered (e.g., drilling a hole, signing a document, entering patient data).
- **Transportation (Arrow →):** Represents physical movement of materials, paperwork, or individuals from one operating location to another via forklift, conveyor, cart, or digital transmission.
- **Inspection (Square □):** Represents verification, examination, or measurement of an item against technical standards, quality criteria, or regulatory rules without altering its physical nature.
- **Delay (Capital Letter D):** Represents an unplanned operational stall, bottleneck queue, or waiting period where items sit idle awaiting the next processing machine or operator.

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- **Storage (Inverted Triangle ∇):** Represents formal, controlled placement of goods in an authorized warehouse, tool crib, or filing archive where authorized requisitions are required for withdrawal.

Process analysis examines the detailed sequence of these five elements across an operation. By calculating the ratio of total operation time to total cycle time (Value-Added Ratio), operations managers identify severe delays and transport inefficiencies, paving the way for streamlined process re-engineering.

Chapter 3: Facility Layout Design and Work Measurement

3.1 Facility Layout Classifications and Optimization

Facility Layout involves the physical arrangement of industrial machinery, operator workstations, storage racks, material pathways, and common utilities within an operational building. An optimal layout minimizes material-handling transit costs, reduces occupational hazards, avoids bottlenecks, and maximizes human productivity.

1. Process Layout (Functional Layout): Machinery and operational services performing identical or functionally similar tasks are clustered together in dedicated departmental bays (e.g., all milling machines in the milling department, all lathe machines in the turning shop, or all cardiac diagnostic gear in cardiology). Best suited for job shops and intermittent batch operations. While providing immense flexibility to handle custom orders, process layouts generate complex crisscrossing material paths and heavy work-in-process (WIP) queues.

2. Product Layout (Line Layout / Assembly Line): Machines and workstations are placed in a fixed, continuous sequence dictated precisely by the progressive manufacturing steps of a standardized product. Raw material enters at one end of the line, moves progressively across balanced workstations, and exits as a completed product at the other. Line balancing is the central engineering challenge: allocating tasks across workstations such that idle time across all stations is minimized.

3. Fixed-Position Layout: The product remains stationary at a permanent geographic point because of its massive physical dimensions, immense weight, or fragile state (e.g., civil bridges, oceanic oil platforms, rockets, or surgical patients). All transforming resources—crews of welders, cranes, testing equipment, and electrical supplies—must be mobilized to and from the stationary workspace.

4. Cellular Manufacturing Layout (Group Technology): A modern hybrid layout that reorganizes factory floors by grouping dissimilar machines into compact, U-shaped manufacturing cells dedicated to producing specific "families" of parts with similar geometric shapes or processing requirements. Cellular layouts combine the machine flexibility of process layouts with the low unit cost and swift cycle times of assembly lines.

5. Service Facility Layouts: Service layouts must balance customer flow efficiency with customer experience and revenue generation:

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- *Office Layouts:* Balancing collaborative open-plan spaces with acoustic privacy cubes and digital communication infrastructure.
- *Retail Layouts:* Strategically directing customer foot traffic to maximize impulse purchasing through grid layouts (supermarkets maximizing shelf space) or free-flow boutique loops (luxury apparel encouraging exploration). High-draw staple items (e.g., milk and bread) are placed deep in the rear to pull shoppers across intermediate aisles.

3.2 Assembly Line Balancing Methodology and Formulation

In product layouts, the central operational task is **Assembly Line Balancing**—the assignment of elemental assembly tasks to sequential workstations such that each station takes approximately the same amount of time, cycle time constraints are satisfied, and total idle balance delay is minimized.

> ```
> Cycle Time (C) = Operating Time Available per Day / Desired Daily Output Volume
> Theoretical Minimum Number of Workstations (N_min) = Sum of All Task Times / Cycle Time
> Line Efficiency (%) = [Sum of All Task Times / (Actual Stations × Cycle Time)] × 100
> Balance Delay (%) = 100% - Line Efficiency (%)
> ```
>
> Where: Task times are derived from method studies, and Precedence Diagrams dictate allowed task order.

Numerical Demonstration of Line Balancing: An electronic assembly plant operates an 8-hour shift (480 minutes or 28,800 seconds) per day and aims to produce 600 audio amplifiers daily. The total sum of elemental task times required to assemble one amplifier is 360 seconds. Following precedence allocation, the operation is configured into 9 physical workstations with a cycle time of 48 seconds.

Cycle Time: 28,800 seconds / 600 units = 48 seconds per unit.
Theoretical Minimum Stations: 360 seconds / 48 seconds = 7.5 → **8 stations** minimum.
Actual Configured Stations: 9 stations.
Line Efficiency: [360 / (9 × 48)] × 100 = [360 / 432] × 100 = **83.33%**.
Balance Delay: 100% - 83.33% = **16.67%**.
This quantitative evaluation demonstrates that 16.67% of total line capacity is lost to station imbalance, providing industrial engineers with an objective metric for task reallocation.

3.3 Work Study: Method Study and Work Measurement

Work Study represents the foundational industrial engineering science, pioneered by Frederick Winslow Taylor and Frank and Lillian Gilbreth, dedicated to systematically examining human work activities to enhance efficiency and establish standardized performance benchmarks. Work study bifurcates into two complementary disciplines:

1. Method Study: The systematic recording and critical examination of existing and proposed ways of doing work, as a means of developing and applying easier, more effective methods and reducing

costs. The standard method study procedure follows the disciplined *SREDIM* sequence:

- **Select:** Identify the operational task, job, or process requiring investigation based on economic importance, bottleneck delays, high hazard risks, or customer complaints.
- **Record:** Document all relevant facts relating to the existing method using process charts, two-handed operator charts, flow diagrams, and simo charts.
- **Examine:** Critically challenge every recorded fact using the questioning framework: Purpose (What is done? Why?); Place (Where is it done? Why there?); Sequence (When is it done? Why then?); Person (Who does it? Why them?); and Means (How is it done? Why that way?).
- **Develop:** Formulate the most practical, ergonomic, economic, and safe method by eliminating unnecessary steps, combining operations, rearranging sequences, and simplifying motions.
- **Install:** Implement the new method as standard standard operating practice, providing formal operator retraining and revised tooling.
- **Maintain:** Monitor the installed method through routine periodic audits to prevent operators from drifting back into obsolete work habits.

2. Motion Study and Therbligs: Developed by Frank and Lillian Gilbreth, motion study analyzes the micro-motions of human body limbs during task execution. The Gilbreths classified all physical human movements into seventeen fundamental units termed *Therbligs* (e.g., Search, Select, Grasp, Transport Loaded, Position, Assemble, Use, Disassemble, Inspect, Release Load, Rest for Overcoming Fatigue). By eliminating non-productive Therbligs (such as unnecessary searching, holding, or awkward reaching), fatigue is minimized and manual output is maximized.

3. Work Measurement (Time Study): The application of specialized techniques designed to determine the time necessary for a qualified, fully trained worker to carry out a specified job at a defined standard rate of performance. The stopwatch time study methodology proceeds through definitive mathematical steps:

```
Observed Time (OT) = Sum of Recorded Cycle Times / Number of Observed Cycles
Normal Time (NT) = Observed Time × (Performance Rating Factor / 100)
Standard Time (ST) = Normal Time × [1 + Total Allowance Fraction]
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Where: Performance Rating benchmarks operator speed against standard pace (100%), and Allowances compensate for personal physiological needs (5%), basic fatigue (4%), and unavoidable shop delays.

Numerical Demonstration of Standard Time Determination: An industrial engineer records the assembly of a miniature circuit breaker over 50 repetitive cycles. The average observed time across all cycles is 2.40 minutes. The operator's observed working pace is evaluated with a performance rating of 115% (working 15% faster than standard pace). Corporate operational policy dictates an aggregate personal and fatigue allowance of 15% of normal time.

Calculation:
Normal Time = 2.40 minutes × (115 / 100) = 2.76 minutes.
Standard Time = 2.76 minutes × [1 + 0.15] = 2.76 × 1.15 = **3.174 minutes** (or 3 minutes and 10 seconds).

This established standard time serves as the objective baseline for assembly line balancing, wage incentive calculations, plant capacity planning, and product standard costing.

3.4 Algorithmic Layout Optimization: CRAFT, ALDEP, and COREL

In complex industrial facilities with dozens of interconnected departments, determining the optimal spatial layout manually becomes mathematically intractable. Industrial engineers deploy computerized layout optimization algorithms:

- **CRAFT (Computerized Relative Allocation of Facilities Technique):** An improvement-type layout algorithm that begins with an existing block layout and an inter-departmental material flow matrix ("From-To Chart"). CRAFT calculates total material-handling transport costs (Distance × Flow Volume × Unit Handling Cost) and systematically evaluates pairwise exchanges of adjacent departments with equal areas or shared boundaries, iteratively converging toward the cost-minimizing spatial configuration.
- **ALDEP (Automated Layout Design Program):** A construction-type layout algorithm that builds a facility layout from scratch using a relationship chart (REL Chart) developed by Richard Muther's Systematic Layout Planning (SLP). Departments are placed sequentially based on closeness ratings: Absolutely Necessary (A), Especially Important (E), Important (I), Ordinary Closeness (O), Unimportant (U), and Undesirable (X).
- **COREL (Computerized Relationship Layout):** Another construction-type algorithm that calculates Total Closeness Ratings (TCR) for all departments, placing the department with the highest TCR at the physical center of the building and sequentially wrapping interacting departments around it.

3.5 Detailed Classification of the 17 Therbligs

Frank and Lillian Gilbreth identified seventeen fundamental elemental motions (Therbligs) that comprise all manual human work. Industrial engineers examine video recordings of assembly tasks to identify and eliminate non-value-adding Therbligs:

Therblig Name	Operational Nature	Engineering Strategy & Elimination Technique
Search (Sh)	Eye or hand actively hunting for an object.	Eliminate completely by providing fixed, labeled bins and transparent organizers.
Select (St)	Choosing one item from several identical items.	Eliminate by pre-sorting and presenting components in single-orientation part feeders.
Grasp (G)	Closing fingers around an object.	Optimize by using vacuum pickups, magnetic grippers, or customized trays.
Transport Loaded (TL)	Moving an object with the hand or arm.	Minimize transit distance by placing supply bins within the normal operator reach zone.

Therblig Name	Operational Nature	Engineering Strategy & Elimination Technique
Position (P)	Aligning an item prior to assembly.	Reduce time by utilizing chamfers, guide pins, and self-locating mechanical stops.
Assemble (A)	Fitting mating parts together.	Essential value-adding step. Optimize using DFMA snap-fits rather than screws.
Hold (H)	One hand gripping an item while the other works.	Eliminate completely. Human hands should never act as vises; deploy mechanical clamps and fixtures.
Rest for Overcoming Fatigue (R)	Periodic pause to restore physiological capacity.	Minimize fatigue by providing ergonomic seating, anti-fatigue mats, and counter-weighted tools.

3.4 Ergonomics and Socio-Technical Job Design

Modern job design transcends mechanical efficiency by integrating **Ergonomics** (Human Factors Engineering) and socio-technical theory. Ergonomics seeks to fit the workplace, tools, and environmental conditions to the physical and cognitive capabilities of human workers, rather than forcing workers to adapt to awkward machinery. Principles include:

- *Anthropometric Workspace Design:* Designing adjustable workbench heights, seating supports, and tool reach envelopes based on 5th to 95th percentile human body dimensions.
- *Environmental Optimization:* Maintaining ambient illumination (500–1000 lux for precision assembly), acoustic noise control (below 85 dB), and climate regulation to prevent physical fatigue.
- *Job Enlargement and Enrichment:* Expanding the horizontal scope of tasks (Job Enlargement) and increasing vertical autonomy, decision-making responsibility, and task identity (Job Enrichment) to combat monotony and enhance psychological motivation.

2.3 Group Technology and the Opitz Coding System

Group Technology (GT) is an operational philosophy that identifies and exploits underlying similarities among manufactured parts and processes to streamline production. In conventional job shops, parts with identical shapes or machining requirements often wander through disconnected departments. Group technology categorizes parts into *Part Families*—clusters of parts that possess similar geometric configurations, dimensions, or manufacturing processing steps.

To systematically categorize components, enterprises deploy alphanumeric classification and coding systems, of which the **Opitz Classification System**, developed by Herwart Opitz of the University of Aachen, is the most celebrated. The Opitz system utilizes a 9-digit alphanumeric code:

- *Form Code (Digits 1 to 5):* Encodes primary geometric shape (rotational vs non-rotational, length-to-diameter ratio), external shapes, internal features (holes, threads), surface machining (flat faces, grooves), and auxiliary holes or gear teeth.

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- *Supplementary Code (Digits 6 to 9):* Encodes operational parameters, including raw material type, original raw material shape, required dimensional accuracy (tolerances), and surface roughness finish.

3.6 Comprehensive Line Balancing via Ranked Positional Weight (RPW) Method

To demonstrate practical assembly line configuration in industrial engineering, consider the assembly of an electric lawnmower comprising eight discrete elemental tasks (A through H). The available operating time is 480 minutes (28,800 seconds) per day, and the required production quota is 400 lawnmowers per day. Elemental task times and precedence relationships are detailed below:

Task ID	Task Description	Duration (Seconds)	Immediate Predecessors	Positional Weight
Task A	Assemble Base Frame	40	None	210
Task B	Mount Electric Motor	30	Task A	170
Task C	Install Drive Axle	50	Task A	140
Task D	Attach Rotary Blade	40	Task B	100
Task E	Install Wheels & Bearings	30	Task C	90
Task F	Connect Wiring Harness	20	Task B	80
Task G	Mount Safety Shroud	40	Task D, Task E	60
Task H	Final Electrical Inspection	20	Task F, Task G	20
Total	**Sum of Task Times**	**270 seconds**	-	-

Step-by-Step RPW Algorithm Resolution:

1. Desired Cycle Time (C): 28,800 operating seconds / 400 units = **72 seconds per unit**.
2. Theoretical Minimum Stations (N_min): 270 seconds / 72 seconds = 3.75 → **4 stations minimum**.
3. Positional Weight Calculation: For each task, its positional weight equals its own duration plus the durations of all downstream follower tasks. For example, Positional Weight of Task A = 40 (A) + 30 (B) + 50 (C) + 40 (D) + 30 (E) + 20 (F) + 40 (G) + 20 (H) = 270 seconds. Tasks are ordered by descending positional weight: A (210), B (170), C (140), D (100), E (90), F (80), G (60), H (20).

4. Workstation Allocation (Cycle Time limit = 72 seconds):

- **Station 1:** Assign Task A (40s) + Task B (30s) = 70 seconds. Idle time = 72 - 70 = 2 seconds.
- **Station 2:** Assign Task C (50s) + Task F (20s) = 70 seconds. Idle time = 72 - 70 = 2 seconds.

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- **Station 3:** Assign Task D (40s) + Task E (30s) = 70 seconds. Idle time = 72 - 70 = 2 seconds.
- **Station 4:** Assign Task G (40s) + Task H (20s) = 60 seconds. Idle time = 72 - 60 = 12 seconds.

5. Evaluation of Line Balancing Performance:
Actual Workstations Formed = 4 stations (matching theoretical minimum).
Total Workstation Time = 4 stations × 72 seconds = 288 seconds.
Total Assembly Time = 270 seconds.
Total Line Idle Time = 288 - 270 = 18 seconds.
Line Efficiency: [270 / 288] × 100 = **93.75%**.
Balance Delay: 100% - 93.75% = **6.25%**.
Managerial Outcome: The RPW heuristic successfully balanced the line into 4 stations achieving an exceptional efficiency of 93.75% with a minimal balance delay of only 6.25%.

3.5 Summary of Operations Design Invariants

Designing operations requires the systemic harmonization of product geometry, process choice, plant layout, and human work systems. By linking concurrent engineering with DFMA, operations streamline product architectures. Selecting the appropriate process archetype along the Product-Process matrix ensures alignment between market demand variety and production volume. Applying method study and time measurement establishes scientific work standards, while ergonomic job design sustains human wellbeing and high operational productivity across multi-year manufacturing lifecycles.

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