ROBOTIC ASSEMBLY LINE BALANCING PROBLEM

Assembly line in manufacturing process comes at last which delivers the finished product with sequence of several tasks. Normally these tasks were performed by humans earlier before the introduction of robots. However, due to ever-changing consumer tastes and to outperform the competitors, many industries started using robots in their assembly line. The main reasons for this change is to improve production rate, efficiency, reduce cost(wastes) and to increase agility towards changing demands. This use of robots in assembly line was called as robotic assembly lines(RAL). Use of robots in industries helped them to reduce labour cost, variability in production, and enhance productivity as robots can work 24/7 all year with no fatigue or illness. Advancements in technology helped this evolution to further replace humans by robots in performing complex tasks too.

Since the introduction of robots in assembly line, robotic assembly line balancing(RALB), and extension of ALB got into interest for many researchers and industries to further optimize their production. This varied from the conventional ALBP as here two sub problems are to be addressed and they are, assignment of task to the given workstations and assignment of different available robots to the workstations.

**General definition of RALBP:**

The general assembly line balancing problem has some objective such as minimising cycle time, cost, etc.., with some constraints such as precedence relation of tasks, number of workstations, etc.., As the robots are accurate in performing tasks, their task times are assumed to be deterministic while solving RALBP. Some other assumptions made by the researchers on solving them were,

1. The precedence relation of tasks are known and the task times depend completely on the type of robot chosen.
2. One workstation comprises only one robot and all types of robot are always ready to use without any capacity and cost limitations.

Further RALBP is classified into several types such as,

1. RALBP TYPE I – Aims at reducing number of workstations by assigning best suited robots and tasks to workstations.
2. RALBP TYPE II – Aims at minimising cycle time with pre-defined number of workstations.
3. RALBP TYPE E – Aims at reducing both cycle time and workstations thus maximising the assembly line efficiency.
4. RALBP TYPE F – Aims at finding feasible solutions for a pre-defined set of workstations and cycle times.
5. RALBP TYPE COST – Aims at monetary and economic aspects of RAL.
6. RALBP TYPE O – Other categories are classified in this type.

Further, the equations and mathematical modelling of RALBP TYPE-I and TYPE-II are elaborated with explaining the notations and equations used. The formulation of Mixed integer programming(MIP) is shown that is used by many researchers to simplify the constraints in the RALBP. Some other metrics to evaluate the complexity of RALBP were also listed in the paper.

**Proposed structure to classify RALBP:**

In RALB, the classifications are based on the structure of the assembly lines. They are MAL(multi manned assembly line), PWAL(parallel workstation), PAL(parallel), UAL(U-shaped), StAL(straight line), 2SAL(two sided), PUL(parallel U-line), PAUL(parallel adjacent U-line), PMAL(parallel multi-manned).

They further subdivided it to concept of 4M. The abbreviation of each M as,

1. Man – RALB could be robot only or human robot collaboration.
2. Machine – Elaborates on the robot related constraints such as hardware and software that affects the assignment of robots to the workstations.
3. Material – RALB can further be classified on the number of products assembled in the line such as single model, multi-model and mixed model assembly lines.
4. Method – RALB is done for both single objective and multi-objective problems. Also different methods use different formulations such as integer linear programming(ILP), mixed-integer programming(MIP), non-linear programming(NLP), etc.., Several techniques are also used to arrive at solution set, and some of them are, exact optimization techniques, using heuristics, meta-heuristics, etc..,

**Straight line assembly line (StAL) (single product):**

1991 (Rubinovitz and Bukchin) – The kick-started the research in the area of RALB. They assumed single product and only one robot on each workstation while solving RALB TYPE I. Their model aimed at reducing the number of workstations with known cycle time by allocating different tasks and robots to different stations.

1993 (Rubinovitz) – addressed the two main objectives of RAL, i.e.., assigning tasks to stations that satisfy the precedence constraints and assigning robots to stations such that efficient solution is found. The search limiting heuristics with branch and bound (B&B) algorithm was proposed to solve complex real world problems.

1995 (Kim and Park) – They considered RALBP TYPE I, where they included several other constraints such as capacity of robot hand tool, storage space, etc.., They proposed ILP using cutting plane algorithm as solution method. This method was able to find the lower bound on the optimal solution.

1997 (Hong and Cho) – They considered two objectives that included robotic assembly line sequencing problem and ALBP. The objective of ALBP was to find minimum number of work stations for a fixed cycle time and assembly sequencing focused on minimising the assembly cost that satisfied the assembly constraints. A simulated annealing (SA) algorithm was used for this purpose.

2006 (Levitin) – This paper focused on RALB TYPE II which aimed at reducing the cycle time with fixed workstations. Genetic algorithm with recursive and consecutive assignment procedures was incorporated and compared. This research concluded that Genetic algorithm with consecutive assignment method produced better results than recursive method.

2009 (Gao) – considered RALB TYPE II. Integer non linear programming (INLP) was formalised with hybridised GA. For large sized problems, the results were promising and outperformed other existing algorithms at that time.

2012 (Nilakantan and Ponnambalam) – The study focused no RALB TYPE II. Local exchange procedure with PSO algorithm was formulated to obtain better solution quality. This was compared with GA with consecutive and recursive assignment methods and results show that the proposed algorithm outperformed them.

2012 (Yoosefelahi) – studies RALBP TYPE II with multiple objectives such as minimising cycle time, robot costs and robot setup costs. MILP model was formulated and meta heuristics (constraint multi objective evolutionary strategy, Pareto archive evolutionary strategy, and hybrid multi objective evolution strategy) were proposed.

2015 (Nilakantan) – studies RALBP TYPE II and tried to optimize energy consumption and cycle time simultaneously. 0-1 integer programming model was introduced and two models were developed namely time-based and energy-based. PSO was used to find solution set. This research concludes that time based model is better than energy based model in terms of the cycle time.

2015 (Nilakantan) – For the same problem type mentioned above, bio inspired algorithm, hybrid cuckoo search and PSO (CS-PSO) is used for larger sized problems. This paper concluded that CS-PSO outperformed PSO.

2016 (Cil) – focused of RALBP TYPE II with mixed model assembly line. Beam search algorithm which used different rules such as, random search, descending minimum positional weights, shortest task time, maximum follower, maximum follower and longest task times, and mixing priority rules were developed. The results conclude that Beam search with mixing priority rules outperformed other combinations.

2017 (Nilakantan) – This paper focuses on RALBP with two objectives (minimising cycle time and assembly cost) with U-shaped and StAL layout. Differential evolution(DE) algorithm was proposed for large sized problems. This concluded that U-Shaped assembly layout produced better solutions than the StAL.

2018 (Borba) – proposed a method to find the lower bound for the RALBP TYPE II problem. Iterative Beam search (IBS) with MILP and branch and bound and remember(BBR) heuristics was proposed. The results were promising to find better solution in an acceptable time.

2019 (Janardhanan) – Considered RALB TYPE II which introduces sequence dependent robot setup times which was always neglected in many other previous research works. In this study, the setup times depend on the previous task and the robot used to perform that task. MILP model was used for small sized problems and Migrating bird optimization (MBO) was used for large sized problems.

2019 (Weckenborg) – This research focused on RALBP TYPE II with deployment of collaborative robots on the assembly line. For this kind of problems, the task time was dependent on the process alternatives (human alone, robot alone, human-robot). MIP for formulated for small sized problems and hybrid GA was used for large sized problems. This study concluded that by incorporating human robot collaboration in assembly line the efficiency, productivity, flexibility and adaptability were improved noticeably.

2019 (Dalle Mura and Dini) – This paper proposed a software based on GA for balancing assembly lines in which humans and robots worked collaboratively. A weighted sum of multiple objectives was used to reduce the complexity of the problem to single objective problem.

2019 (Weckenborg and Spengler) – Developed a MILP model for HRC under consideration of ergonomics of human workers. The type of problem was RALBP TYPE II. Cost efficient configurations were realised from this approach.

**U shape assembly line (UAL):**

2016 (Nilakantan and Ponnambalam) – This research was the first to study RALBP TYPE II with UAL layout. This differed from StAL as the task assignment can be of forward assignment or backward assignment. They used 1-0 IP and PSO with consecutive method assignment to solve larger sized problems and concluded that UAL showed better results compared to StAL in terms of reduced cycle time.

2016 (NIlakantan) – This research focused on RALBP TYPE E, where the main focus was to reduce the energy consumption with given number of workstations and cycle time. Two meta-heuristics (PSO and DE) were compared in this study. They concluded that DE arrived at better results compared to PSO in gaining higher line efficiency and lower cycle time. However, PSO outperformed DE in terms of minimising energy consumption.

2016 (Rabbani) – This research considered the MOO RALBP TYPE II, whose objectives were to minimise cycle time, sequence dependent setup cost, robot setup cost, and robot purchasing cost. They further made their study complex by considering mixed model products. For small sized problems they formulated MILP whereas for larger sized problems they used meta-heuristics such as multi objective PSO (MOPSO), and Non dominated sorting GA (NSGA II). They concluded that NSGA II generated solutions close to pareto optimal front than the MOPSO.

2017 (Nilakantan) – This study compared StAL and UAL in RALBP TYPE II. Three algorithms were employed and compared. Two PSO algorithms (PSO+CONSECUTIVE, PSO+RECURSIVE) outperformed the hybrid GA and they also showed that UAL with PSO+CONSECUTIVE produced better solutions than all the other combinations in terms of cycle time reduction.

**2 sided assembly line (2SAL):**

2014 (Aghajani) – They were the ones who kick-started the research in RALBP TYPE II with 2SAL layout. In this study setup times and sequence-dependent setup times were considered while allocating tasks between stations. Simulated annealing (SA) was employed for this problem and was proved that SA was more effective in finding the solutions quicker.

2016 (Li) – This research discusses on the RALBP TYPE II with 2SAL where two robots face each other in a mated station and work on different tasks simultaneously. Due to the NP-hardness of the problem, they developed co-evolutionary PSO (C-PSO) to solve and arrive at better solutions. They bench marked this algorithm with several other algorithms such as ABC, PSO, ASA, GA, etc.., and showed that C-PSO outperformed the others.

2016 (Li) – They pointed out the importance of energy consumption and its reduction under RALBP TYPE II in the 2SAL problem. They considered two objectives simultaneously (minimising cycle time and energy). They used restarted simulated annealing (RSA) which employed local search and restarting mechanism. This was bench marked against two single objective algorithms which focused on the objectives separately. This study concludes that the RSA was better than those algorithms in terms of convergence and spread of solutions in the pareto optimal front.

2018 (Li) – This study focuses on the same type of problem as mentioned above. This differed from previous studies by modifying the DCS to a cooperative co-evolutionary cuckoo search(CoCS) algorithm. This was compared with several other algorithms such as ABC, PSO, GA, etc.., and the results concluded that this algorithm outperformed the others in many instances.

**Research Findings:**

The contributions in the RALBP field were summarised in a form of table with detailed contributions of each and every author in a chronological order. Further, for users easy understanding a flow chart of the same was drafted in this paper.

Since the study started on RALBP, only 33 articles were published till date since 1991(30 years). The research on this field was less and skyrocketed recently (2015-2019). Since the introduction of StAL on 1913, 6 other layouts were developed as mentioned earlier. The most researched layout out of them was StAL.

Though mixed model RAL is beneficial in manufacturing as it allows to assemble several products according to the demand, not many research papers were published on this area. Most of the research were focused on single product assembly line(80%).

Since 1997, most of the researchers started using deterministic variable task times that were determined on the types of robots. This was due to the development in technology that resulted in invention of many different robots that can perform all the tasks. Although, there were many types of RALBP, the most researched area was RALBP TYPE II. Most of the researchers focused on reducing the cycle time that ultimately increased the productivity and reduced the time to market of the products.

The study of multi objective RALBP further gained more interest by many researchers as this was not addressed by many papers at that time. Mathematical models were used to describe the relations between the different objectives and to handle the constraints effectively. As the size of the problem increased, meta-heuristics started dominating the other methods. Many meta-heuristics were developed to tackle this NP-hardness of the RALBP.

Introduction of Cobots(collaborative robots) to the assembly line, created a new trend in the research area of RALBP. This use of cobots in the assembly line showed better results and gained interest by many industries. As this area of research is quite new, only few papers were published since 2019.

Many real life constraints such as tools assignment, tool space optimization, etc.., were not addressed in most of the papers and this could be the future in the study of RALBP. Also only one paper was published that addressed the environmental issue (carbon footprint) by the robots in RAL.

**Future research directions:**

Almost all the research on RALBP assume fully automated assembly line which requires huge investments. Not all the industries were capable to do such investments and still many of the industries slowly started to introduce robots in their assembly lines. So the study on human robot collaboration assembly line could be a great research area as many industries opt them as they are easy and require less investment.

The studies that included cobots in the assembly line mostly preferred only one robot in a workstation. Research study on multiple robots and humans working in parallel could be a great area of research. As humans started working alongside robots, study of ergonomics and real life constraints such as human fatigue, sequence dependent setup times, tool and accessory changing, part transportation between stations, etc.., can be included in RABLP as no one has ever did that previously due to its high complexity.

The RALBP are mostly based on single product assembly line. Study on mixed and multi model assembly line could be novel in this area of research. Also most of the studies were done only on RALBP TYPE II, which again creates a research gap in other types of RALBP.

Most industries focus on many objectives while designing assembly lines rather than just one. Research on Multi objective optimizations could be more relevant to real life problems. As introduction of multi objectives create more complexity, many meta-heuristics were developed. From the recent studies, hybrid meta heuristics showed better results than meta heuristics. So study on hybrid meta heuristics on solving multiple objectives could create a way for finding better pareto optimal solution sets.