## Stream of Variation for Multi-stage Assembly

Prof. Hu pioneered the research area of compliant, non-rigid part assembly by developing the "Stream of Variation" theory for predicting and diagnosing quality variation in multi-stage assembly systems [1]. Prior approaches for assembly quality control were based on univariate, sampled-data which did not take into consideration the relationships among various quality features measured on an assembly. With multivariate data made available by the coordinate measurement machines and in-line vision systems, Dr. Hu first introduced Principal Component Analysis (PCA) to the diagnosis of quality variation in such multi-stage assembly systems [2]. Measurements from multiple locations on the assembly are clustered together according to the correlation among them and the clusters are compared with the assembly hierarchy. Then the patterns of assembly variation for each clustered group of locations are identified and displayed based on the variance of the principal components and their eigenvectors. This represents a scientifically sound yet physically intuitive way of explaining assembly variation. Perceptron, Inc. {https://perceptron.com/solutions/automated-metrology} incorporated the multi-variate analysis and PCA algorithm into its software offering for automotive in-line metrology.

From the variation patterns, the root causes of variation are then systematically identified and removed. The application of PCA and associated methodologies helped the U.S. auto manufacturers significantly reduce auto body dimensional variation and shorten launch time. Under a grant from the NIST Advanced Technology Program, "2 mm Program - Development of Advanced Systems and Technologies for Controlling Dimensional Variation in Automobile Body Manufacturing" (1992 – 1996), Dr. Hu and his team worked closely with Chrysler, General Motors and several automotive suppliers in successfully implementing the systematic methodology in the automobile assembly plants**.** See figure 2 as an example of the reduction of variation in an assembly plant.

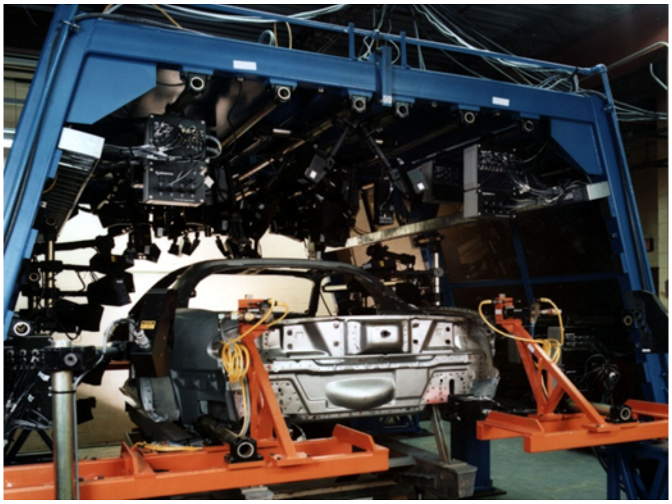


Figure 1. In-line machine vision system measuring a car body.

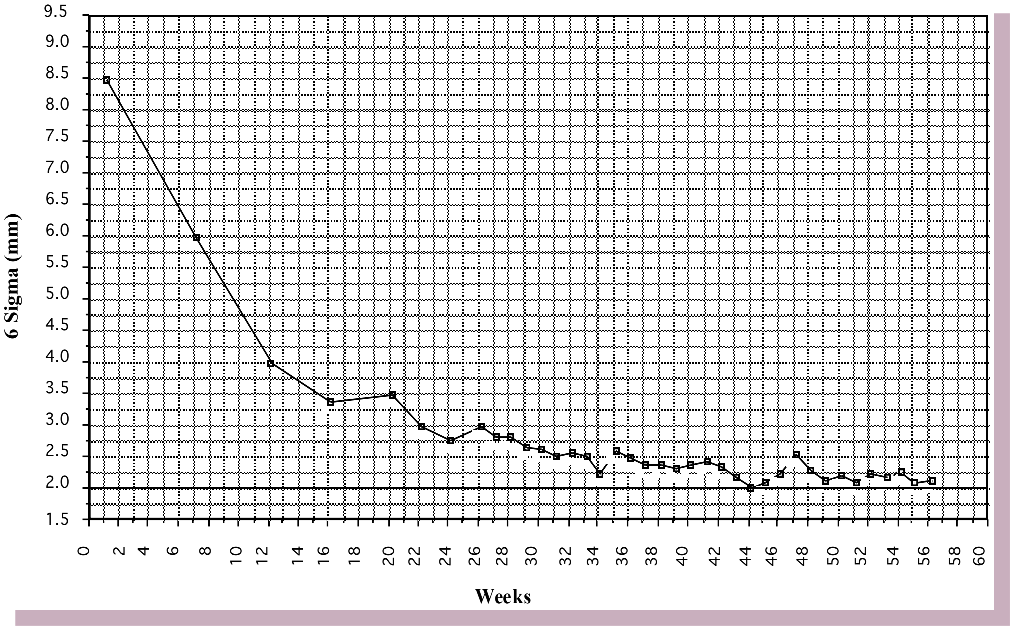
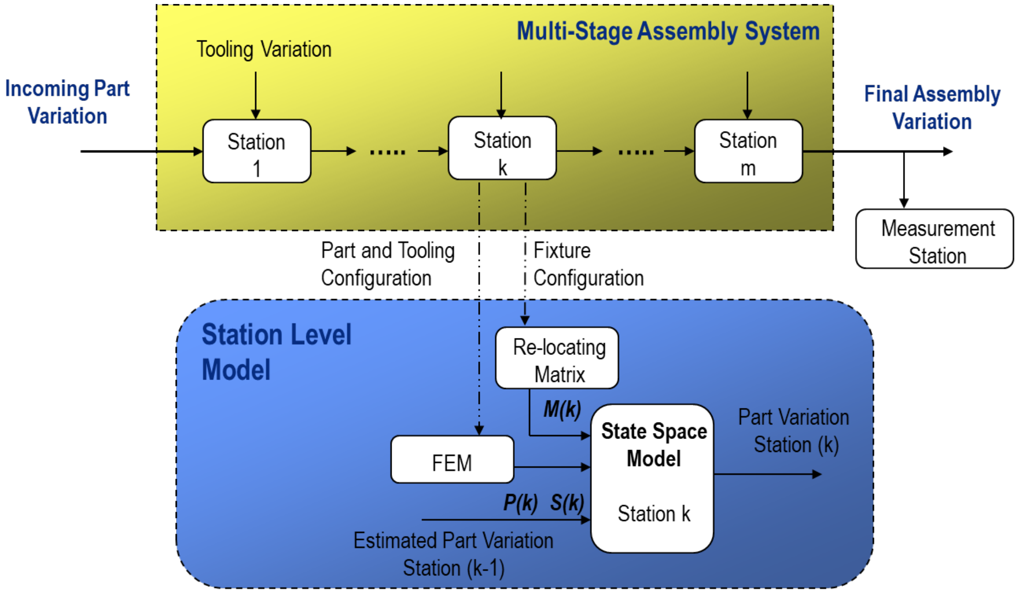


Figure 2. Reduction of auto-body assembly variation

Independent retrospective study of the ATP project by researchers from MIT summarize the economic impact of project {See section on Auto Body Manufacturing Assembly, page 22 – 23. https://www.yumpu.com/en/document/read/29341397/overall-project-performance-nist-advanced-technology-program}. NIST estimates that it increased the U.S. gross domestic product by $186 million.

To move the variation reduction efforts upstream to design, Prof. Hu and his students developed new models for predicting the propagation of variation in multi-stage compliant assembly systems by innovatively fusing engineering structural analysis with advanced statistics [3, 4, 5]. Existing methods for predicting assembly variation before 1992 were based on the assumption of rigid bodies. But sheet metal parts can deform during assembly when subjected to clamping and welding due to part non-rigidity. These deformations and subsequent spring back after releasing the clamps and weld machines cause dimensional changes, making rigid body based variation analysis invalid for sheet metal parts. Thus, Prof. Hu and his students developed a generalized method for variation analysis of non-rigid part assembly by combining finite element analyses with multivariate statistics. Using finite element analysis, a mechanistic model was established to relate the assembly deformation to component variation. Then multivariate statistical method was applied to the mechanistic model to calculate assembly variation [3, 4, 5]. Finally, both station level and system level models were developed. His paper on "Modeling Variation Propagation of Multi-Station Assembly Systems with Compliant Parts" [6] won the best paper award in the 2001 ASME Design for Manufacturing Conference for its original contribution.

Hu also successfully extended the methods of compliant assembly to performance modeling of electronic packaging and fuel cell assembly [7, 8, 9].



*Liu and Hu, (1997); Camelio, Hu and Ceglarek, (2003)*

Figure 3. Modeling of multi-stage assembly system with non-rigid parts.

## Selected Publications

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1. SJ Hu, (1997), "Stream-of-variation theory for automotive body assembly", *CIRP Annals-Manufacturing Technology* 46 (1), 1-6.

2. SJ Hu, SM Wu, (1992),"Identifying sources of variation in automobile body assembly using principal component analysis", *Transactions of NAMRI/SME* 20, 311-316

3. SC Liu, SJ Hu, TC Woo, (1996), "Tolerance analysis for sheet metal assemblies", *ASME Journal of Mechanical Design* 118, 62-67.

4. SC Liu, SJ Hu, (1997), "Variation simulation for deformable sheet metal assemblies using finite element methods", *ASME Journal of Manufacturing Science and Engineering*, 119, 368-374

5. W Cai, SJ Hu, JX Yuan, (1996), "A variational method of robust fixture configuration design for 3-D workpieces", *ASME Journal of Manufacturing Science and Engineering* 119, 593 – 602.

6. J Camelio, SJ Hu, D Ceglarek, "Modeling variation propagation of multi-station assembly systems with compliant parts", ASME Journal of Mechanical Design 125, 673-681.

7. M Chin, KA Iyer, SJ Hu, (2004), "Prediction of electrical contact resistance for anisotropic conductive adhesive assemblies", *IEEE Transactions on Components and Packaging Technologies*, 27 (2), 317-326.

8. L Zhang, Y Liu, H Song, S Wang, Y Zhou, SJ Hu, (2006), "Estimation of contact resistance in proton exchange membrane fuel cells", *Journal of Power Sources* 162 (2), 1165-1171.

9. Y Zhou, G Lin, AJ Shih, SJ Hu, (2007) "A micro-scale model for predicting contact resistance between bipolar plate and gas diffusion layer in PEM fuel cells", *Journal of Power Sources* 163 (2), 777-783.

## Smart Manufacturing

With the advent of industrial-internet of things, rich data are being develop from machines, systems and factories. These data can be used to monitor and control manufacturing processes and improve quality. Prof. Hu has done extensive work in using on-line signals and process features for monitoring the quality of important manufacturing processes.

His earlier work was focused on automotive welding/joining processes, including resistance spot welding, and gas metal arc welding [1, 2, 3]. A framework for inteilliegent welding systems was proposed in a review paper pubished in 2020 [4].

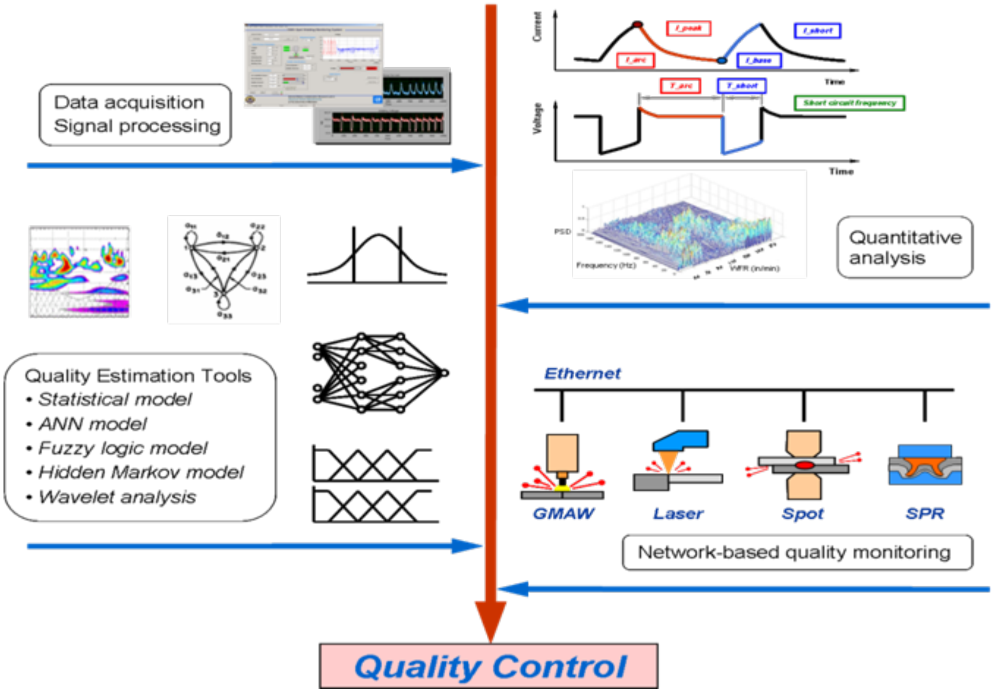


Figure 5. A frame work for smart manufacturing in materials joining.

With lithium ion batteries, traditional fusion welding techniques cannot be applied due the material dissimilarity of battery tabs. As such, ultrasonic welding was considred a good alternative. A new in-line non-destructive quality evaluation system was developed for quality monitoring in ultasonic welding of battery cells using multiple sensor signals. The most important features were selected systematically using advanced feature selection algorithms and matched with the physics of the ultasonic welding process. SPC and Mahalanobis distance were integrated together to monitor the welding process performance [5, 6, 7, 8]. The implementation such a system in a battery assembly plant has resulted in a signinificant reduction of manual inspection (80%) while ensuring consistency battery welds.

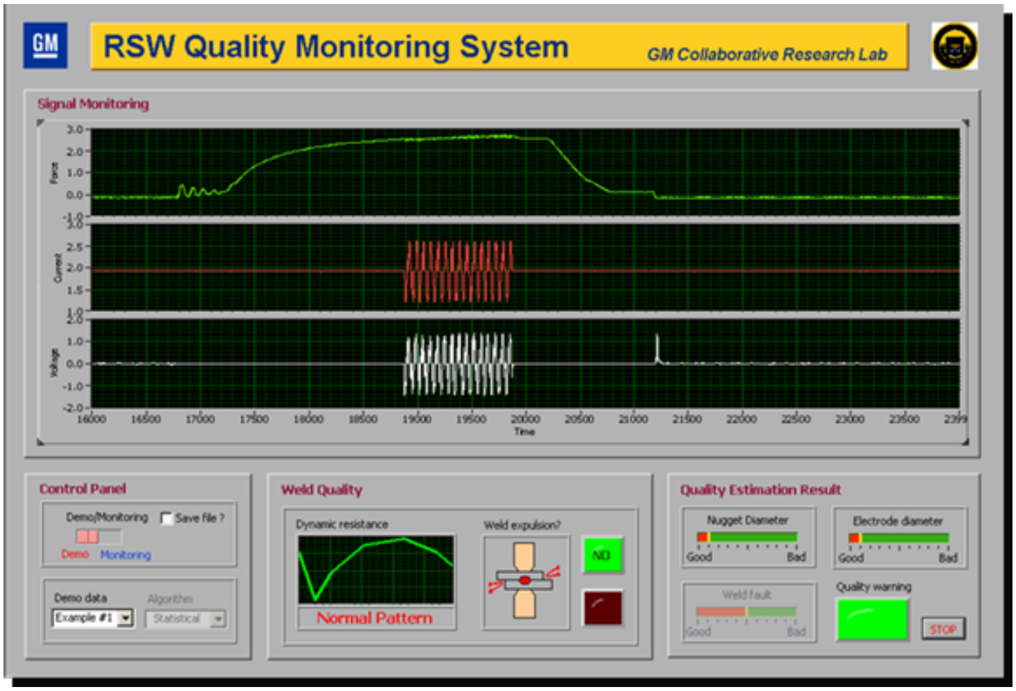


Figure 6. A smart manufacturing quality monitoring system for lithium-ion battery assembly.

Recently, Hu and his team adopted the smart manufacturing methods have been applied to ultrasonic welding of carbon fiber composite materials [9, 10, 11].

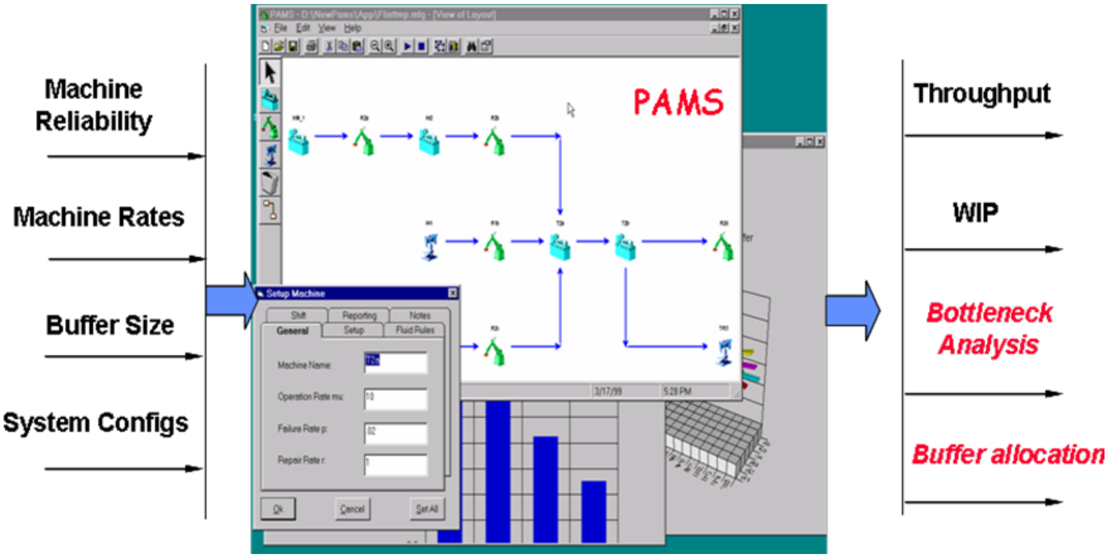
### Selected Publications

1. W. Li, **S.J. Hu**, and J. Ni, (2000), "A Method for On-Line Quality Prediction of Resistance Spot Welding," *ASME J. of Manufacturing Science and Engineering*. Vol. 122, pp.511-512.
2. YX. Chu, **S.J. Hu**, W.K. Hou, P.C. Wang and S. P. Marin, 2004, "Signature Analysis for Quality Monitoring in Short Circuit GMAW," *Welding Journal*, December, pp.336s-343s.
3. Ersoy, U.; **Hu, S.J.**; Kannatey-Asibu, E. (2008), "Observation of arc start instability and spatter generation in GMAW," *Welding Journal* (Miami, Fla), v 87, n 2, February, p 51-s-56-s.

4. B. Wang, **S.J. Hu**, L. Sun, T. Freiheit, (2020), Intelligent welding system technologies: State-of-the-art review and perspectives," *Journal of Manufacturing Systems,* volume 56, 373-391.
5. Chenhui Shao, K Paynabar, TH Kim, JJ Jin, SJ Hu, JP Spicer, H Wang, JA Abell, (2013) "Feature selection for manufacturing process monitoring using cross-validation," *Journal of Manufacturing Systems*. Vol. 32, No. 4, 550-555.
6. S.S. Lee, T.H. Kim, **S.J. Hu**, W.W. Cai, J.A. Abell, (2015), "Analysis of Weld Formation in Multilayer Ultrasonic Metal Welding Using High-Speed Images," *ASME Journal of Manufacturing Science and Engineering*, 137 (3), 031016.
7. W. Guo, C. Shao, T.H. Kim, **S.J. Hu**, J.J. Jin, J.P. Spicer, H. Wang, (2016), "Online process monitoring with near-zero misdetection for ultrasonic welding of lithium-ion batteries: An integration of univariate and multivariate methods," *Journal of Manufacturing Systems* 38, 141-150.
8. W.G. Guo, J.J. Jin, **S. J. Hu**, (2019), "Profile Monitoring and Fault Diagnosis Via Sensor Fusion for Ultrasonic Welding," *Journal of Manufacturing Science and Engineering, 141 (8).*
9. Y. Li, T.H. Lee, M. Banu, **S.J. Hu**, (2020), "An integrated process-performance model of ultrasonic composite welding based on finite element and artificial neural network," *Journal of Manufacturing Processes, April. https://doi.org/10.1016/j.jmapro.2020.04.033*
10. L. Sun, C. Tan, **S. J. Hu,** P. Dong, T. Freiheit, (2021), "Quality detection and classification for ultrasonic welding of carbon fiber composites using time-series data and neural network methods," *Journal of Manufacturing Systems,* Volume 61, Pages 562-575
11. L. Sun, **S.J. Hu**, T Freiheit, (2021), "Feature-based quality classification for ultrasonic welding of carbon fiber reinforced polymer through Bayesian regularized neural network," *Journal of Manufacturing Systems*, volume 58, 335-347.

**Manufacturing Systems:**

In manufacturing systems, Prof. Hu pioneered the work in designing innovative system configurations for quality, productivity and responsiveness [1, 2, 3]. He successfully led a group of researchers at the Engineering Research Center for Reconfigurable Manufacturing Systems at the University of Michigan ( https://erc.engin.umich.edu/) to develop the fundamental science and methodologies for designing and improving the performance of manufacturing systems. These fundamental sciences are then implemented in a set of highly efficient mathematical methods and algorithms to analyze configurations quickly and accurately. A software package, PAMS – Performance Analysis of Manufacturing Systems, was successfully developed for designing system configurations, evaluating system throughput, and identifying bottlenecks for improvement. PAMS also contains optimization routines to calculate the sizes of buffers and optimally place them in manufacturing systems. These models and algorithms have been applied to machining systems and automotive body assembly systems at GM, Ford, Chrysler and other companies, and are helping them improve their overall system performance at both the design and operations phases.



Machine Name: [illegible]
Operation Rate mu: 10
Failure Rate p: .02
Repair Rate r: 1

Figure 4. A software system for analyzing manufacturing system configuration for productivity.

From 2011- through 2019, Prof. Hu and his students have been developing automotive lithium-ion battery manufacturing [4]. Lithium batteries are a critical enabling technology for electric and plug-in electric vehicles which have received great attention from industry and governments as we try to reduce the dependence on fossil fuels. A battery “Assembly System Configurator” has been developed for battery assembly system design. Given battery cell configurations (size, weight and shape, e.g., cylindrical vs. prismatic), pack requirements (volume, power requirements, etc) and aided by a pre-designed assembly machine database, the Configurator generates the assembly system layouts and assigns assembly tasks to the stations. It also selects the assembly machines for the stations by minimizing total investment cost. The Configurator has been validated and has been used by engineers at General Motors to generate assembly system concepts for various battery pack designs.

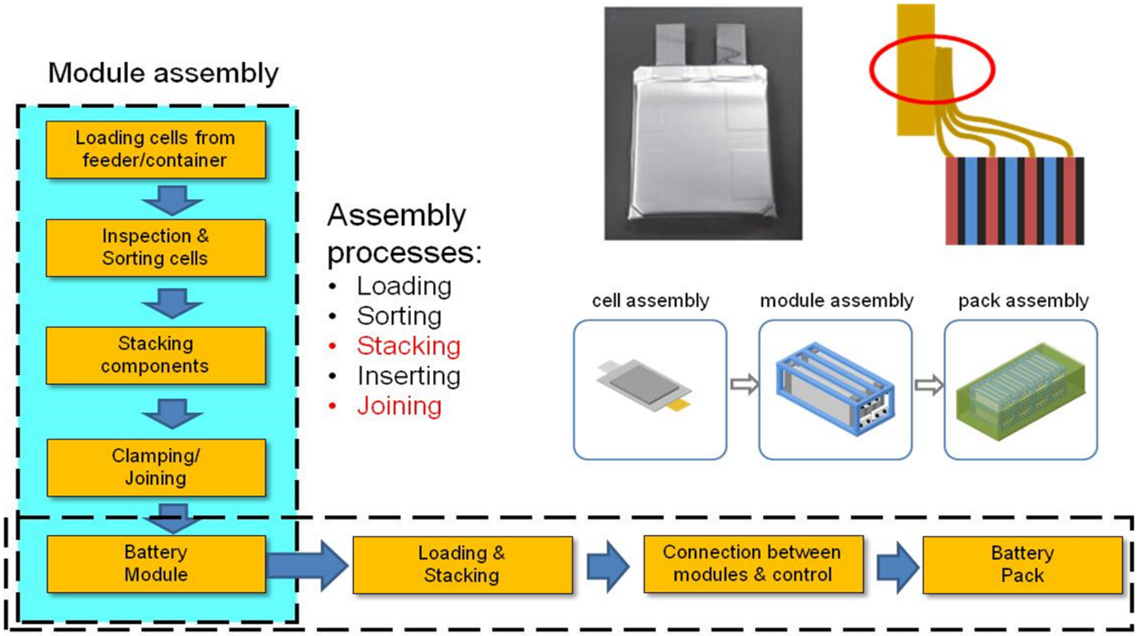


Figure 5. A lithium-ion battery assembly system configurator

## Selected Publications

1. Y Koren, SJ Hu, TW Weber, (1998), “Impact of manufacturing system configuration on performance”, *CIRP Annals-Manufacturing Technology* 47 (1), 369-372.

2. Maier-Speredelozzi, S.J. Hu, (2002), "Selecting manufacturing system configurations based on performance using AHP”, *Transactions of NAMRI/SME*.

3. R.F. Webbink, S.J. Hu, (2005), "Automated generation of assembly system-design solutions”, *IEEE Transactions on Automation Science and Engineering*, Vol. 2, No. 1, 32-39.

4. S Li, H Wang, **SJ Hu**, YT Lin, JA Abell, (2011), "Automatic generation of assembly system configuration with equipment selection for automotive battery manufacturing", *Journal of Manufacturing Systems* 30 (4), 188-195.