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Can Machine Learning Improve Portfolio Risk-Adjusted Performance?

A Smart Beta Case Study

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Investors have often asked how best to allocate into smart beta strategies to improve risk diversification. In this paper, we demonstrate how hierarchical clustering techniques could play a role in this pursuit.

In long-only equity allocations, the dominant risk typically emanates from market beta. In a bid to achieve better diversification, investors have grown increasingly accustomed to allocating into smart beta — or factor — strategies to smooth their investment journey. Aside from diversification, investors also attempt to generate outperformance by timing their allocations across different smart beta strategies, aware that the performance of individual factors are sensitive to the prevailing macroeconomic cycles (for example, see Ung and Luk (2016)[1]).

Once the objectives of the allocation are established, there is the additional consideration of how best to build the portfolios to achieve these objectives. In recent years, a growing body of literature has emerged on whether the allocation should be built bottom up at the stock level or top down at the strategy level. The aim of this paper is neither to assess the merits of pursuing a top-down or bottom-up strategy, nor evaluate whether smart beta is best used to diversify risk or enhance performance. Instead, our goal is to examine whether **machine learning insights can play a role in improving risk diversification in a multi-factor smart beta allocation through the use of the hierarchical clustering techniques.**

What is the Hierarchical Risk Clustering Algorithm?

First proposed by de Prado in 2016,[2] the hierarchical risk clustering algorithm makes use of graph theory and unsupervised machine learning techniques to build diversified portfolios by acknowledging the hierarchical nature of the investment universe. The rationale behind the algorithm is to address deficiencies in the Markowitz mean-variance optimisation procedure that is commonly used to build investment portfolios and from which the standard efficient frontier is generated.

One such deficiency relates to the instability of the output generated by the traditional optimisation procedure, insofar as small deviations in the expected returns will produce drastically different portfolio outcomes. This can be a major problem, especially because expected returns derived from investor expectations are often extrapolated and do not generally predict returns well (Greenwood and Schleifer (2014)[3]). In an attempt to deal with inaccurate expected return forecasts, some practitioners advocate the use of risk-based algorithms, such as equal risk contribution or maximum decorrelation, among others, as the main way to conduct portfolio allocation.

However, these approaches come with their own challenges. In particular, the shortcoming pertains to the technical aspect of how Markowitz's optimisation problems are generally dealt with. Invariably, these problems are tackled with quadratic programming methodologies that necessitate the inversion of a well-conditioned (positive, semi-positive) covariance matrix. A well-conditioned covariance matrix is required to ensure that the solutions generated from it do not become too sensitive to perturbations in the input data.

Sensitivity to minor changes in the input data can be an acute issue, especially when it comes to including strongly correlated investments in the same portfolio where any benefits of diversification would be offset by estimation errors. For these reasons, de Miguel et al (2009)[4] conclude that risk-based approaches have performed poorly out of sample and, in 2016, **de Prado introduced the hierarchical risk parity approach to address the flaws associated with the traditional mean-variance optimisation procedure as well as to recognise the hierarchical nature of investment assets.** Since then, other researchers put forward various enhancements to the original methodology.

Among the adaptations, the one that gained most traction was advanced by Raffinot (2018),[5] which combines de Prado's original hierarchical risk parity approach and Raffinot's (2017)[6] hierarchical clustering-based asset allocation approach. The main steps for this adapted approach are: 1) tree clustering by selecting the optimal number of clusters, and 2) top-down recursive bisection and assignment of weights to each of the assets in the portfolio.

In the first step, the algorithm segregates the assets into different clusters on the basis of a similarity measure, which is often risk- or correlation-based,[7] and clustering linkages — which determine how the clusters should be formed. The clustering linkage we have used here is the Ward linkage[8] and it analyses the variances of the clusters rather than measuring distances directly, thereby minimising the variance between clusters. To avoid having too many clusters, which can lead to problems of statistical overfitting, gap analysis is used to decide on the appropriate number of clusters. This is reflected where the 'tree' is cut in Figures 3, 4 and 5.

The second step involves recursive bisection and the assignment of weights to each asset. We first compute the weights for each cluster. To do that, we progressively descend through the waterfall structure from the top of the tree (hierarchy) and, at each point, the tree bisects into two sub-clusters. From an initial weighting scheme,[9] the cluster weights are adjusted by an alpha factor that reflects the ratio of the similarity measure between the two clusters. After this step, the individual asset weights within each cluster are correspondingly calculated.[10]

Diversified Risk-Adjusted Outperformance

As highlighted above, the cluster and individual asset weights can be based on countless measures and, depending on whether the focus is on risk or the type of risk, different risk-return profiles can be achieved. The purpose here is not to ascertain the 'best' measure to be used in the weighting scheme but rather to assess if there are any potential benefits to using a hierarchical clustering approach in the allocation of smart beta building blocks. To do this, we have adopted an equal-weight weighting scheme in the analysis below.

To evaluate the risk-return profile of the hierarchical clustered smart beta portfolio, we created annually rebalanced hierarchical clustered portfolios using a variety of regional smart beta building blocks across different time horizons and compared them with an equally weighted smart beta portfolio. The building blocks in scope for the analysis include factors, such as the Dividend Aristocrats, value, quality, momentum, low volatility, and size. The regions we consider include Europe, Pan Asia, UK and the US.

The results in Figure 1 show that **the hierarchical clustered smart beta portfolio outperformed the equally weighted smart beta portfolio** by between 0.36% and 1.81%, on an absolute basis, and this is generally consistent across multiple time horizons. The outperformance also holds on a risk-adjusted basis. This is because the strong performance from the hierarchical clustered portfolio came not only from the strength of the absolute return but also from a reduction in the risk.

Indeed, the level of risk reduction was present not only at the overall portfolio level but also in the tail risk, as evidenced by a lower level of conditional value at risk for the hierarchical clustered smart beta portfolio. The only exception appeared to be in the last five years but, even then, the risk-adjusted return for the clustered hierarchical smart beta portfolio was still stronger than that of the equal-weighted portfolio, while the other risk metrics were largely comparable.

An important benefit that results from better diversification is obviously a reduction in the overall portfolio risk level. However, a reduction in risk per se does not mean that the portfolio is well diversified, especially when it invests all of its capital in a few of the least (historically) volatile assets. To reap the genuine benefits of diversification, it is vital to observe both a reduction in risk and a lack of concentration at the same time and this is what we can see in Figure 1. **The hierarchical clustered smart beta portfolio generally achieved a higher level with risk reduction than the equally weighted portfolio and the diversification metrics — such as the diversification risk and the number of correlated bets — did not deteriorate markedly.**

Figure 1
Risk-Return Results of Hierarchical Clustered Portfolio against the Equally Weighted Portfolio

Full study period (2006–2023)	Return (Annualised) (%)	Risk (Annualised) (%)	Risk-Adjusted Return	Max Drawdown (%)	Diversification Ratio*	No. of Effective Bets**	Max Risk Contribution (%)	Conditional VaR (95%) (%)
Hierarchical Clustered Equal-Weighted Smart Beta Portfolio	5.01	17.03	0.29	-57.65	1.16	22.68	0.61	-6.02
Equally Weighted Smart Beta Portfolio	4.08	18.09	0.23	-60.79	1.16	23.03	0.48	-6.43
First sample (2006–2014)								
Hierarchical Clustered Equal-Weighted Smart Beta Portfolio	3.39	18.57	0.18	-57.65	1.15	22.63	0.58	-6.65
Equally Weighted Smart Beta Portfolio	3.03	20.11	0.15	-60.79	1.15	22.96	0.48	-7.35
Second sample (2014–2023)								
Hierarchical Clustered Equal-Weighted Smart Beta Portfolio	6.88	15.48	0.44	-33.30	1.19	22.71	0.83	-5.35
Equally Weighted Smart Beta Portfolio	5.44	16.08	0.34	-35.58	1.20	23.22	0.44	-5.48
Last 5 years (2018–2023)								
Hierarchical Clustered Equal-Weighted Smart Beta Portfolio	5.92	20.36	0.29	-35.77	1.14	22.86	0.84	-7.14
Equally Weighted Smart Beta Portfolio	4.12	20.23	0.20	-35.88	1.15	23.02	0.29	-7.12

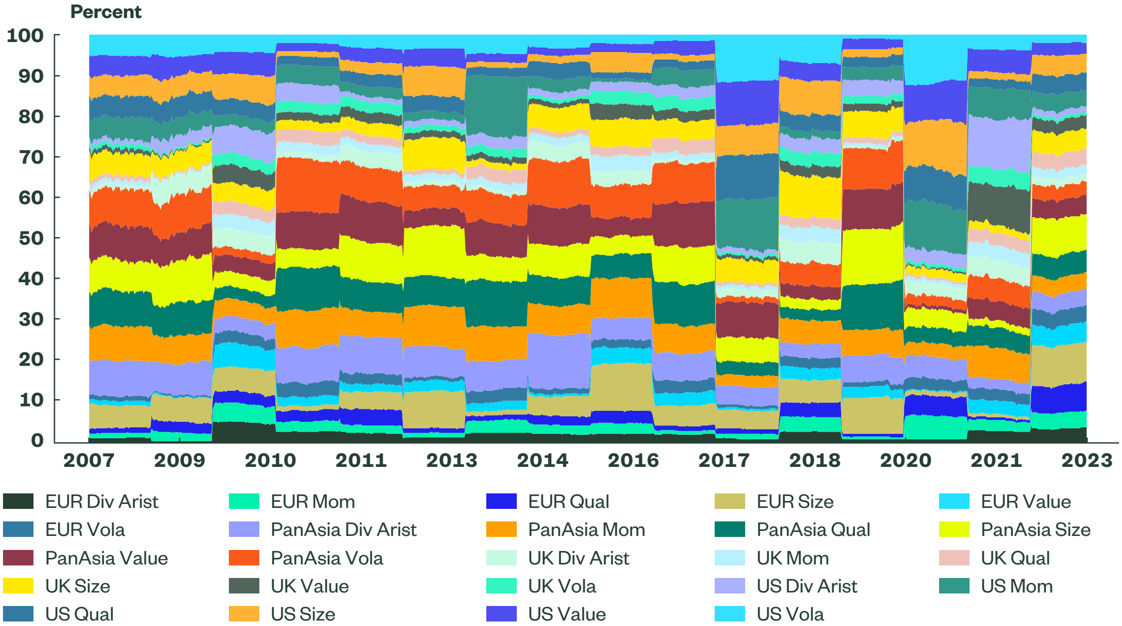
Source: State Street Global Advisors, Bloomberg Finance L.P Results are based on weekly return data between August 2006 and April 2023. *Diversification ratio is computed as the weighted average risk of each asset, adjusted by portfolio risk. **The number of effective bets (No. of Effective Bets) represents the average number of uncorrelated investments computed in line with methodology introduced in Meucci et al (2015).[11]

Asset Allocation

To understand why the hierarchical clustered portfolio outperformed, it is important to delve into the asset allocations over the entire period as well as certain key market events, such as before and after the Global Financial Crisis (i.e. 2007 and 2008). Alongside this, we will also analyse the asset allocation of the latest rebalance.

Between 2006 and 2023, the hierarchical clustered smart beta strategy delivered a higher risk-adjusted return than the equally weighted benchmark portfolio. During the entire study period, it is worth highlighting that there was regular bias towards the Pan Asian smart beta building blocks (see Figure 2). More often than not, the Pan Asian exposures are grouped together as an entirely separate cluster, possibly because the median correlation of that cluster to other regional clusters was relatively low (appx. 0.71).

Figure 2
Allocations of the Equally Weighted Clustered Hierarchical Smart Beta Portfolio Over the Study Period



Source: Bloomberg Finance L.P., State Street Global Advisors. Data from July 2006 to April 2023. It is not possible to invest in directly an index. "US Div Arist" is represented by the S&P High Yield Dividend Aristocrats Index. "UK Div Arist" is represented by the S&P UK High Yield Dividend Aristocrats Index. "EUR Div Arist" is represented by the S&P Euro High Yield Dividend Aristocrats Index. "PanAsia Div Arist" is represented by the S&P Pan Asia Dividend Aristocrats Index. "US Vola" is represented by the MSCI USA Minimum Volatility Index. "UK Vola" is represented by MSCI United Kingdom Minimum Volatility Optimized In GBP Index. "EUR Vola" is represented by the MSCI Europe Minimum Volatility Optimzied in Euro Index. "PanAsia Vola" is represented by the MSCI AC Asia Pacific Minimum Volatility Optimized In USD Index. "US Mom" is represented by the S&P 500 Momentum U.S. Dollar Index. "EUR Mom" is represented by the MSCI Europe Momentum Index. "UK Mom" is represented by the Invesco UK Broad Price Momentum Index. "PanAsia Mom" is represented by the STOXX Asia/Pacific 600 Ax Momentum Index. "US Size" is represented by the MSCI Daily TR Gross Small Cap USA Local Index. "EUR Size" is represented by the MSCI Europe Small Cap Gross Total Return Local Index. "UK Size" is represented by the MSCI UK Small Cap Gross Total Return Local Index. "PanAsia Size" is represented by the MSCI AC Asia Pacific Small Cap Loc Index. "US Value" is represented by the S&P 500 Enhanced Value Net Total Return Index. "EUR Value" is represented by the STOXX Europe 600 Ax Value Index. "UK Value" is represented by the MSCI UK Value Weighted Index. "PanAsia Value" is represented by the STOXX Asia/Pacific 600 Ax Value Index. "US Qual" is represented by the MSCI USA Sector Neutral Quality Index. "EUR Qual" is represented by the MSCI Europe Quality Index. "UK Qual" is represented by the Invesco UK Broad Quality Index. "PanAsia Qual" is represented by the STOXX Asia/Pacific 600 Ax Quality Index.

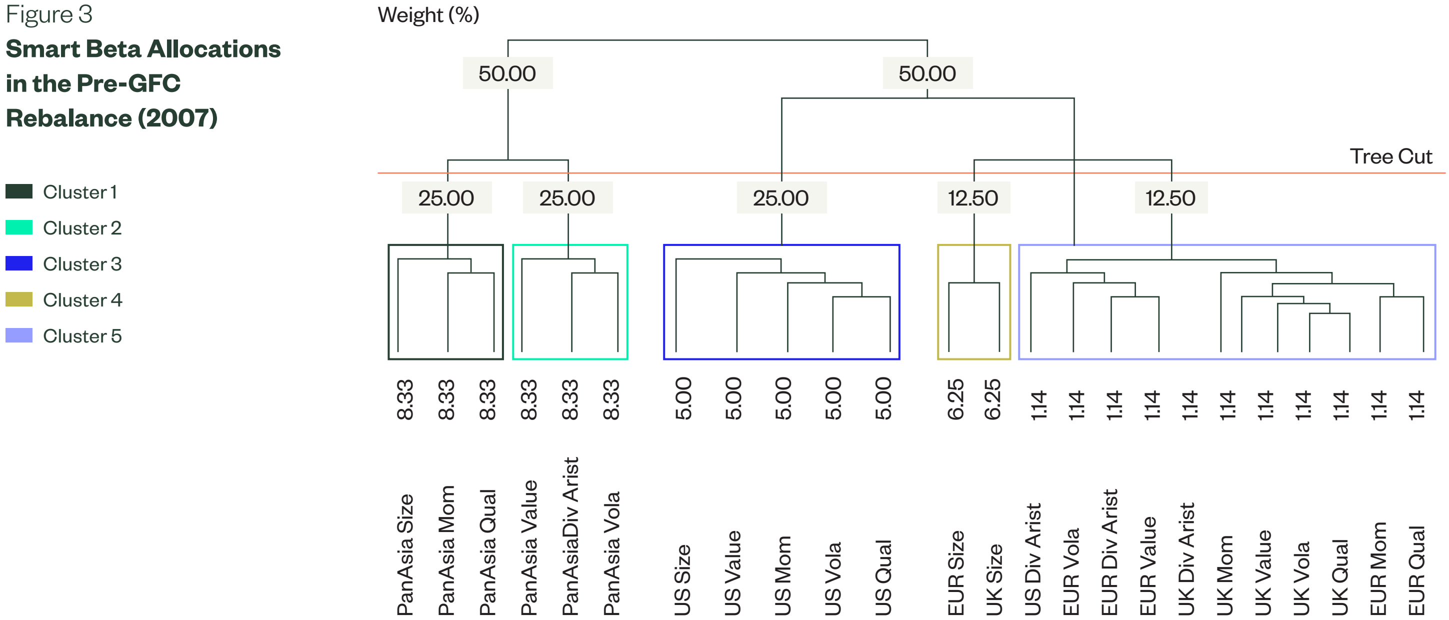
Weight Allocation before and after the Global Financial Crisis

Next, we scrutinise the asset allocation before and after the Global Financial Crisis (GFC) and examine the rebalances in 2007 and 2009. Turning first to the rebalance prior to the GFC, it is worthwhile noting that the two clusters containing all the Pan Asian smart beta building blocks had a total weight of 50% (see Figure 3). The next biggest cluster assembled all the US smart beta exposures and had a cumulative weight of 25%, followed by a separate cluster that only had Europe and UK size exposures. The last cluster encompassed all other remaining Europe and UK smart beta building blocks and had a total weight of 12.5%.

From the perspective of asset allocation, a high weight was placed on the two clusters consisting of the Pan Asian smart beta building blocks. This was followed by European and UK small caps, which are often regarded as procyclical factors. Interestingly, the last cluster, with a total of 11 building blocks, attributes modest weights to more defensive factors — notably, the Dividend Aristocrats range — as well as other European and UK quality, momentum and volatility factors. In this rebalance, there is also a wide range of weights assigned across different assets, from 1.14% to 8.33%.

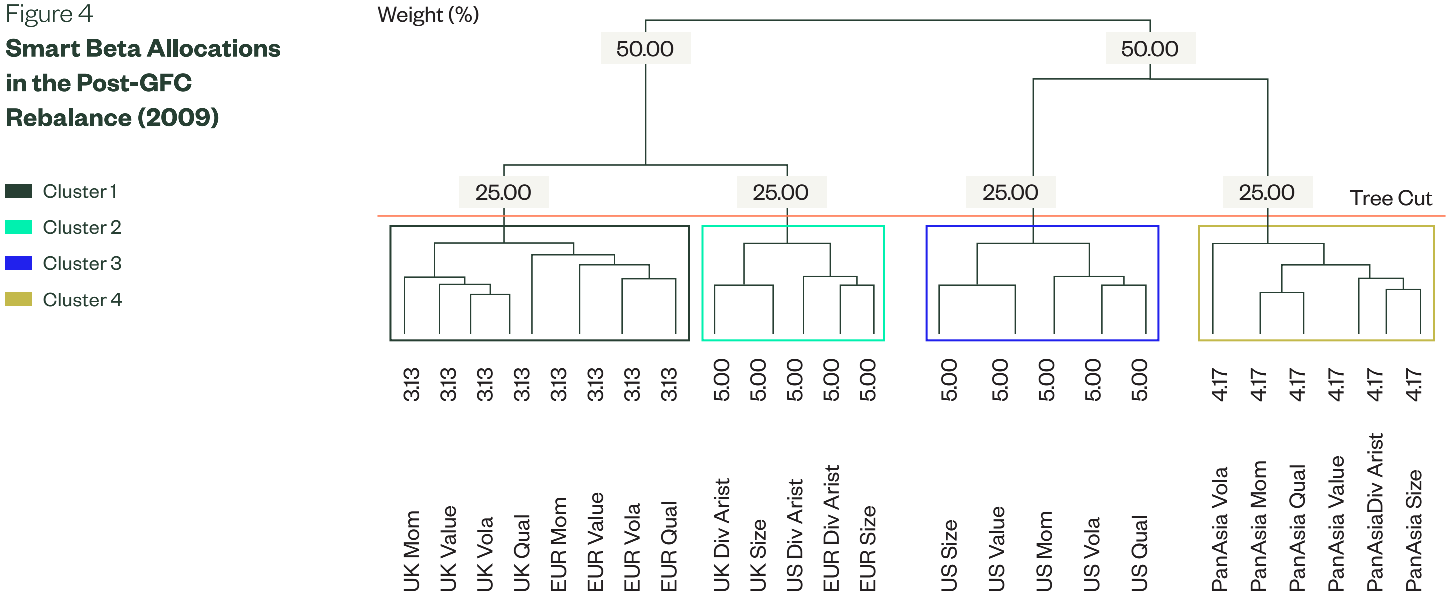
The situation reversed somewhat in the direct aftermath of the GFC (see Figure 4). In the 2009 rebalance, there is a higher weight being allocated to defensive factors — such as the Dividend Aristocrats across the UK, US and Europe — as well as other remaining US smart beta factors. Once again, all the Pan Asian smart beta building blocks are grouped under one cluster and all share the same weights. Of particular note is that the range between the highest and lowest asset weight is much tighter (between 3.13% and 5.00%) compared to what we witnessed in the rebalance before the GFC.

Figure 3
Smart Beta Allocations in the Pre-GFC Rebalance (2007)



Source: Bloomberg Finance L.P., State Street Global Advisors. Data from July 2006 to April 2023. It is not possible to invest in directly an index. “US Div Arist” is represented by the S&P High Yield Dividend Aristocrats Index. “UK Div Arist” is represented by the S&P UK High Yield Dividend Aristocrats Index. “EUR Div Arist” is represented by the S&P Euro High Yield Dividend Aristocrats Index. “PanAsia Div Arist” is represented by the S&P Pan Asia Dividend Aristocrats Index. “US Vola” is represented by the MSCI USA Minimum Volatility Index. “UK Vola” is represented by MSCI United Kingdom Minimum Volatility Optimized In GBP Index. “EUR Vola” is represented by the MSCI Europe Minimum Volatility Optimzied in Euro Index. “PanAsia Vola” is represented by the MSCI AC Asia Pacific Minimum Volatility Optimized In USD Index. “US Mom” is represented by the S&P 500 Momentum U.S. Dollar Index. “EUR Mom” is represented by the MSCI Europe Momentum Index. “UK Mom” is represented by the Invesco UK Broad Price Momentum Index. “PanAsia Mom” is represented by the STOXX Asia/Pacific 600 Ax Momentum Index. “US Size” is represented by the MSCI Daily TR Gross Small Cap USA Local Index. “EUR Size” is represented by the MSCI Europe Small Cap Gross Total Return Local Index. “UK Size” is represented by the MSCI UK Small Cap Gross Total Return Local Index. “PanAsia Size” is represented by the MSCI AC Asia Pacific Small Cap Loc Index. “US Value” is represented by the S&P 500 Enhanced Value Net Total Return Index. “EUR Value” is represented by the STOXX Europe 600 Ax Value Index. “UK Value” is represented by the MSCI UK Value Weighted Index. “PanAsia Value” is represented by the STOXX Asia/Pacific 600 Ax Value Index. “US Qual” is represented by the MSCI USA Sector Neutral Quality Index. “EUR Qual” is represented by the MSCI Europe Quality Index. “UK Qual” is represented by the Invesco UK Broad Quality Index. “PanAsia Qual” is represented by the STOXX Asia/Pacific 600 Ax Quality Index.

Figure 4
Smart Beta Allocations in the Post-GFC Rebalance (2009)

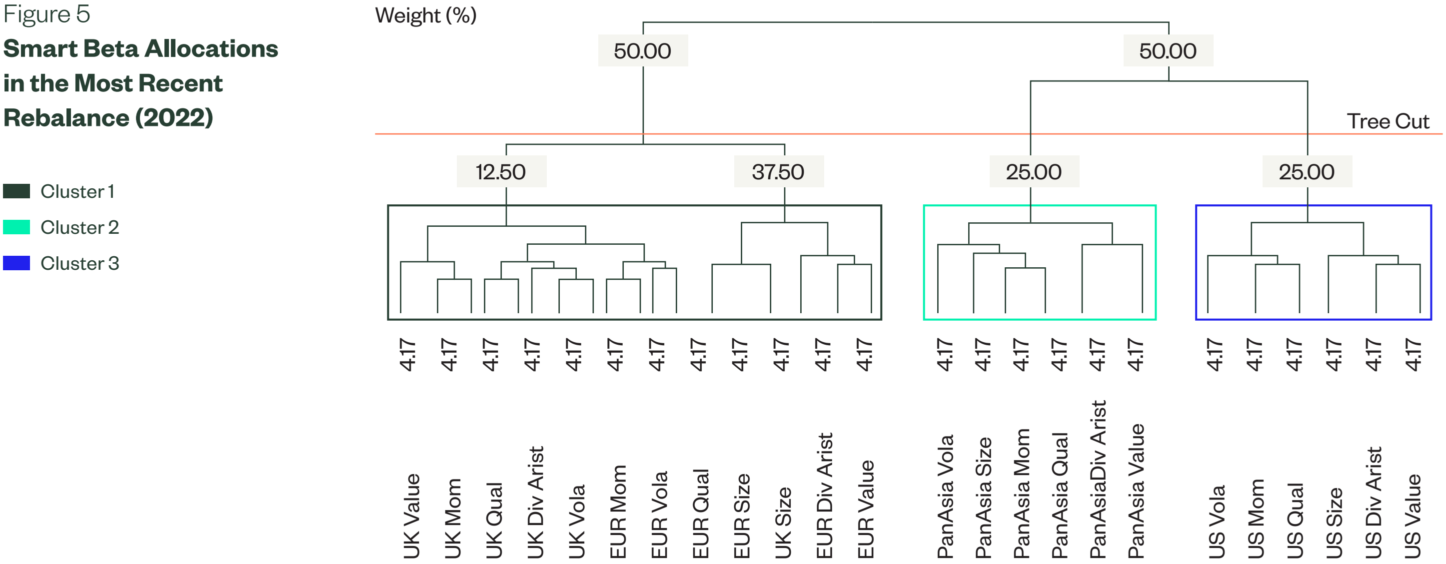


Source: Bloomberg Finance L.P., State Street Global Advisors. Data from July 2006 to April 2023. It is not possible to invest in directly an index. "US Div Arist" is represented by the S&P High Yield Dividend Aristocrats Index. "UK Div Arist" is represented by the S&P UK High Yield Dividend Aristocrats Index. "EUR Div Arist" is represented by the S&P Euro High Yield Dividend Aristocrats Index. "PanAsia Div Arist" is represented by the S&P Pan Asia Dividend Aristocrats Index. "US Vola" is represented by the MSCI USA Minimum Volatility Index. "UK Vola" is represented by MSCI United Kingdom Minimum Volatility Optimized In GBP Index. "EUR Vola" is represented by the MSCI Europe Minimum Volatility Optimzied in Euro Index. "PanAsia Vola" is represented by the MSCI AC Asia Pacific Minimum Volatility Optimized In USD Index. "US Mom" is represented by the S&P 500 Momentum U.S. Dollar Index. "EUR Mom" is represented by the MSCI Europe Momentum Index. "UK Mom" is represented by the Invesco UK Broad Price Momentum Index. "PanAsia Mom" is represented by the STOXX Asia/Pacific 600 Ax Momentum Index. "US Size" is represented by the MSCI Daily TR Gross Small Cap USA Local Index. "EUR Size" is represented by the MSCI Europe Small Cap Gross Total Return Local Index. "UK Size" is represented by the MSCI UK Small Cap Gross Total Return Local Index. "PanAsia Size" is represented by the MSCI AC Asia Pacific Small Cap Loc Index. "US Value" is represented by the S&P 500 Enhanced Value Net Total Return Index. "EUR Value" is represented by the STOXX Europe 600 Ax Value Index. "UK Value" is represented by the MSCI UK Value Weighted Index. "PanAsia Value" is represented by the STOXX Asia/Pacific 600 Ax Value Index. "US Qual" is represented by the MSCI USA Sector Neutral Quality Index. "EUR Qual" is represented by the MSCI Europe Quality Index. "UK Qual" is represented by the Invesco UK Broad Quality Index. "PanAsia Qual" is represented by the STOXX Asia/Pacific 600 Ax Quality Index.

Weight Allocation in the Most Recent Rebalance (2022)

Turning to the most recent rebalance, we observe once again that the Pan Asian smart beta building blocks are grouped together in a single cluster. As with the rest of the building blocks, they are mostly categorised under their respective regions. The most curious observation here is that the smart beta exposures across all regions carry the same weight (see Figure 5) and there is no particular overweight or underweight in any particular exposure.

Figure 5
Smart Beta Allocations in the Most Recent Rebalance (2022)



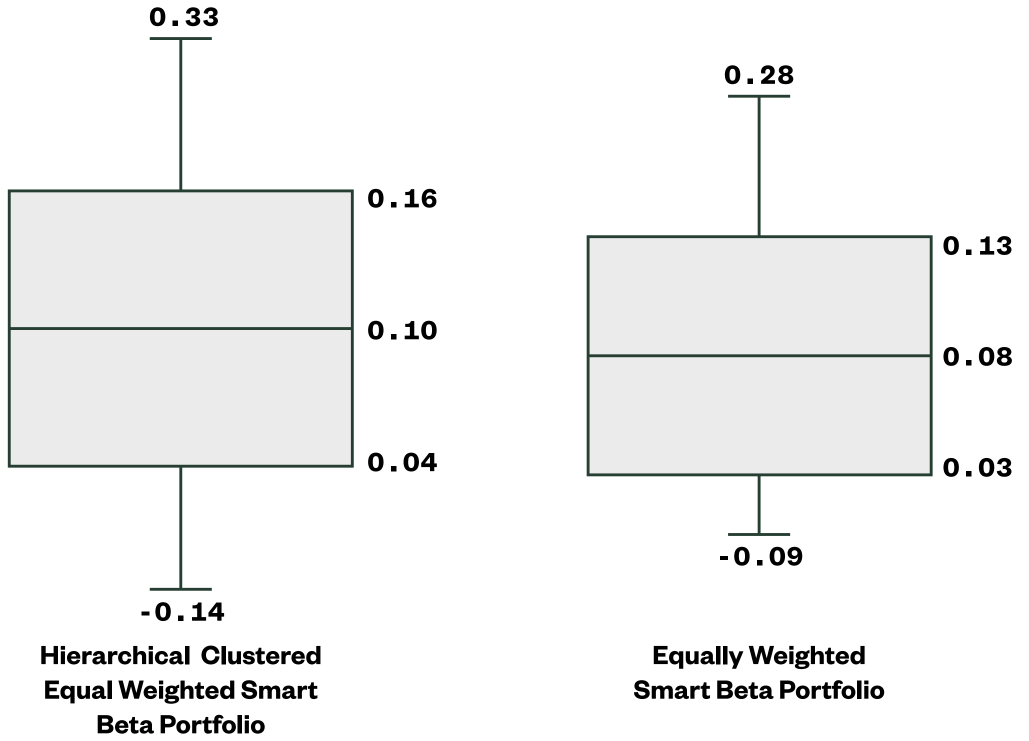
Source: Bloomberg Finance L.P., State Street Global Advisors. Data from July 2006 to April 2023. It is not possible to invest in directly an index. “US Div Arist” is represented by the S&P High Yield Dividend Aristocrats Index. “UK Div Arist” is represented by the S&P UK High Yield Dividend Aristocrats Index. “EUR Div Arist” is represented by the S&P Euro High Yield Dividend Aristocrats Index. “PanAsia Div Arist” is represented by the S&P Pan Asia Dividend Aristocrats Index. “US Vola” is represented by the MSCI USA Minimum Volatility Index. “UK Vola” is represented by MSCI United Kingdom Minimum Volatility Optimized In GBP Index. “EUR Vola” is represented by the MSCI Europe Minimum Volatility Optimzied in Euro Index. “PanAsia Vola” is represented by the MSCI AC Asia Pacific Minimum Volatility Optimized In USD Index. “US Mom” is represented by the S&P 500 Momentum U.S. Dollar Index. “EUR Mom” is represented by the MSCI Europe Momentum Index. “UK Mom” is represented by the Invesco UK Broad Price Momentum Index. “PanAsia Mom” is represented by the STOXX Asia/Pacific 600 Ax Momentum Index. “US Size” is represented by the MSCI Daily TR Gross Small Cap USA Local Index. “EUR Size” is represented by the MSCI Europe Small Cap Gross Total Return Local Index. “UK Size” is represented by the MSCI UK Small Cap Gross Total Return Local Index. “PanAsia Size” is represented by the MSCI AC Asia Pacific Small Cap Loc Index. “US Value” is represented by the S&P 500 Enhanced Value Net Total Return Index. “EUR Value” is represented by the STOXX Europe 600 Ax Value Index. “UK Value” is represented by the MSCI UK Value Weighted Index. “PanAsia Value” is represented by the STOXX Asia/Pacific 600 Ax Value Index. “US Qual” is represented by the MSCI USA Sector Neutral Quality Index. “EUR Qual” is represented by the MSCI Europe Quality Index. “UK Qual” is represented by the Invesco UK Broad Quality Index. “PanAsia Qual” is represented by the STOXX Asia/Pacific 600 Ax Quality Index.

Robustness Tests

To probe whether the hierarchical clustered portfolio can be expected to deliver strong performance “out of sample” as it did “in sample,” we carry out additional robustness tests. The tests involve examining whether the hierarchical clustered smart beta portfolio would still beat the equally weighted portfolio if we assumed that the returns of the various smart beta building blocks were correlated, normally distributed random numbers. In addition to this, randomly selected return shocks were applied to the returns of selected smart beta building blocks to test the robustness of the hierarchical clustered portfolio in challenging market circumstances.

The results from the boxplot in Figure 6, which are derived from 500 simulations, suggest that the risk-adjusted return of the hierarchical clustered portfolio was stronger than that of the equal-weighted portfolio. This implies that the hierarchical clustering algorithm may have useful applications when it comes to achieving better risk-adjusted return and risk diversification.

Figure 6
Simulated Risk-Adjusted Return of the Clustered Hierarchical Smart Beta Portfolio Against the Equal-Weighted Portfolio Over the Entire Study Period (500 Simulations)



Source: State Street Global Advisors, Bloomberg Finance L.P., data are from 2006–2023.

Endnotes

1 Ung and Luk (2016), What Is in Your Smart Beta Portfolio? A Fundamental and Macroeconomic Analysis, Journal of Index Investing.

2 de Prado (2016), Building Diversified Portfolios that Outperform Out-of-Sample, Social Science Research Network.

3 Greenwood, R.M., & Shleifer, A. (2013). Expectations of Returns and Expected Returns. ERN: Expectations in Economic Theory & Markets, Oxford University Press.

4 De Miguel, Garlappi, & Uppal, (2009). Optimal versus naive diversification: How inefficient is the 1/N portfolio strategy? The review of Financial studies, 22(5), 1915–1953.

5 Raffinot (2018), The Hierarchical Equal Risk Contribution in Portfolio, AXA IMI.

6 Raffinot (2017), Hierarchical Clustering-Based Asset Allocation, Journal of Portfolio Management.

7 A number of possible dependency or risk measures can be used, including Pearson correlation, Spearman rho, drawdown-at-risk, among others.

8 Other linkage methods — such as single, ward, average and complete — can be used. The Ward linkage method minimises the increase in the sum of squared error when two clusters are joined.

9 Other starting weighting schemes are also widely used including variance-weighted or volatility-weighted. For an initial weighting scheme of equal weight, no alpha adjustment linked to the similarity measure is made to the intra-cluster weights.

10 This is typically done on the basis of risk measures, such as inverse variance, but other types of risk weighting (e.g. volatility) and equal weighting are also common.

11 Meucci et al (2015). Risk Budgeting and Diversification Based on Optimized Uncorrelated Factors. ERN: Optimization Techniques; Programming Models; Dynamic Analysis (Topic).

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