ASSET RISK EVALUATION USING SHAPLEY VALUE

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Abstract

This paper proposes a method to evaluate the risk of an individual asset in a portfolio using game theory notions. Shapley value is a solution concept of cooperative game theory that divides overall utility of a coalition among the players. It can be shown that it is the only possible fair division, meaning that it satisfies the so-called Shapley’s axioms which offer the mathematical representation of fairness. It takes into account the marginal contribution of a player – their contribution to each possible coalition, compared to a coalition without that player. This concept has been used in many fields to assess the fair division of utility, but also to find a fair cost division among entities participating in a project. Even though variance is the most-commonly used risk measure of an asset, there are many other measures that can be used. There are advantages and drawbacks to each measure, and choosing the best one for asset risk is still an open question. It is well known that, when assessing the risk of an individual asset, one must take into account its connection to the other assets on the market. The aim of this paper is to offer a way to represent the risk of an asset as a single measure but still taking into account its connection within the market. This will be achieved using Shapley's value of an asset, where the risk will be treated as a cost that needs to be divided among assets. Using this methodology, it will be determined to what extent individual asset contributes to total risk of a portfolio. The method will be evaluated using the Zagreb Stock Exchange data. Taking into account the advantages of this approach, the authors hope that this measure has its place in portfolio analysis and determining the key components of market risk.

Keywords: Shapley value, risk assessment, portfolio risk

JEL classification: C71, G11

Introduction

Risk determination is one of the most important tasks of portfolio management. Despite all the efforts to construct a risk measure which will reflect theoretically desirable properties, there is still no consensus on such a measure. It is well-known that, when formulating portfolio, it is not sufficient to focus only on measures of risk of each individual asset – one must also consider relations between assets in the portfolio. Different directions of asset returns can mean lower overall risk than the sum of individual risk measures. Markowitz was the first to realize the importance of asset interactions in his famous “Portfolio selection” paper (Markowitz, 1952). He proved that, if risk is measured as a variance of an asset or a portfolio, then negative covariance between assets can be beneficial as it reduces the portfolio
variance. To this day, variance is still the most frequently used risk measure due to its simplicity, especially in theoretical analysis. Over the years this risk measure provoked a series of criticisms leading up to numerous new proposals (Liang and Park, 2010). Still, any attempt to determine the risk of an asset as an independent market object provides only partial risk measure since it does not incorporate the above-mentioned benefits of accounting its influence on risk of a portfolio. Risk valuation that does not acknowledge this influence always misjudges the true risk that is relevant for investment decisions as it ignores the benefits of diversification. Including this information into a risk measure can produce much more informative and useful tool for asset validation and portfolio decision making. Such a measure needs to divide the overall portfolio risk among assets in a fair way that reflects all the risk that asset transmits through the entire portfolio. Besides negative ones, it also needs to take into account possible positive effects on portfolio risk reduction.

Cooperative game theory analyses behavior of entities (players) and possible benefits of cooperating instead of playing for their own gain. Forming a coalition (as opposed to separated contest) can produce overall utility that exceeds the sum of individual utilities in a disjoined game. The question of central importance in cooperative game theory is, if players cooperate, in what way should they divide achieved utility (Ferguson, 2014). Division needs to be fair, meaning that it should reflect the strength of each individual player participating in a coalition. Depending on properties that one expects from this division, there are many different solution concepts that offer the answer. The best known solution concept is the so-called Shapley value that satisfies Shapley’s axioms of fairness (Leyton-Brown and Shoham, 2008). Shapley value assigns the part of cooperative utility to each player. This concept can be applied to many different problems, such as dividing utility among workers in a team, the strength of a politician in a party, or a party in a parliament (Ferguson, 2014). It can also be applied to determine the significance of a path in a graph, such as a road in a road system, and to measure influential nodes in a social network (Narayanam and Narahari, 2011). It can also be applied to estimate benefits of each education level (Sliskovic and Peric, 2017). Shapley value is not restricted to dividing the gain of a coalition. The same concept can also be used to divide what we consider to be a cost, for example the cost of building a road system (Bird, 1976). In recent years, it is being used to fairly divide the risk in insurance theory, the operational risk of a company (Mitic, Hassani, 2018) or the risk of a particular institution on a financial market (Drehmann and Tarashev, 2013; Cao, 2014). It is not surprising that the same method is proposed for sharing the risk of a portfolio among the assets in the portfolio.

The aim of this paper is to explore the possibilities of Shapley value risk determination in a Croatian stock market. We suggest one possible setup that ensures the fair comparison of risk measures when using Shapley value methodology. We present a model for adequate risk assessment, in a first-ever such research on the Croatian and other Balkan markets. The results presented here should prove helpful for adjusting expectations in similar markets. The rest of the paper is organized as follows. Section 2 summarizes previous research on this topic and other similar topics. In section 3 we give a short overview of Shapley value properties and calculation procedure. In section 4 we present the results obtained and discuss the findings. This section also presents the problems of this method, possible modifications and the obstacles in implementation. Finally, section 5 concludes the paper with future research suggestions.

**Literature review**
Shapley value was first used to allocate the gain obtained by working together, but its application was later expanded to problems of allocating cost or blame. This led to a series of suggestions for practical implementation of this theory, among others for operating cost division in insurance industry (Lemaire, 1984). This proposal sparked expansion of research in actuarial community that finally led to exploring the possibility of using this tool for cost allocation in a portfolio of risks in insurance. Afterwards, this idea of allocating risk among portfolio or risky subjects was first applied in systemic risk measuring and risk decomposition among institutions in a financial system, followed by measuring a risk of and asset in an asset portfolio.

The research of Shapley value approach in portfolio analysis is in its infancy. Terraza and Mussard (2007) applied Shapely value using several French securities and a Gini coefficient as an underlying risk measure. Mussard and Terraza (2008) and Colini-Baldeschi, Scarsini and Vaccari (2018) propose possible theoretical setup for this methodology application and corresponding solutions. Kocak (2014) constructed a game-theoretical environment using different risk level stocks from Financial Times and Stock Exchange. In this environment related payoffs were structured by consulting stock exchange experts, and Shapely value was used to suggest the optimal portfolio. Auer and Hiller (2018) used simulations to show that Shapley value risk division can lead to a better risk estimate since this risk measure can do a better job explaining the so called low-risk puzzle, i.e. empirical findings that suggest that lower risk investment opportunities tend to outperform the high-risk counterparts. This is not in accordance with financial market theory and it is suspected to be a result of a poorly chosen risk measure. Shalit (2017) used optimal Markowitz global minimum variance portfolio to calculate the Shapley value risk measure for six classes of US assets using Ibbotson SBBI data. He suggested two possible approaches. The first one uses the variance of global minimum variance portfolio for each subset of assets when calculating marginal contribution of an asset to risk. We find this approach to be inadequate since it compares risks at different yield levels. Alternatively, he proposes that marginal contribution should be calculated using portfolio from efficient frontier with a fixed expectation. This raises the question of choosing the expectation level. Also, since some subsets of assets are not able to achieve this level of expected yield, or they are able to achieve higher levels, this approach seems to be unfair what is in contradiction to original idea of obtaining the fair risk division.

Methodology

Game theory is used to examine the interaction between rational individuals (players) and to assess their options in a given situation. It is an umbrella term for different analytical methods and solution concepts used to determine the best possible outcome and to propose the optimal decision in a conflicting environment in which every individual wants to maximize its utility. Depending on whether the player are in conflict or they collaborate, game theory can be divided in cooperative and non-cooperative. While the non-cooperative game theory focuses on decision making in a conflict situation in which each player plays as an individual, cooperative game theory examines the possible surplus utility in case they collaborate. It also offers solution concepts for division of acquired utility.

The basic assumption of cooperative game theory is that there are no obstacles in forming a coalition. Players are free to decide whether they want to play alone or join a coalition and possibly achieve greater utility (Ferguson, 2014). Formally, let \( n \geq 2 \) denote the number of players in a game and let \( N = \{1,2,\ldots,n\} \) denote the set of all players. Any subset \( S \) of \( N \),
\( S \subseteq N \) is called a coalition. An empty set \( \emptyset \) is by convection also considered to be a coalition and it is called an empty coalition. In case all players form a coalition, i.e. \( S = N \), we refer to it as a grand coalition. Game in a coalition form is defined by the set of players and by the real-valued function \( v : \mathcal{P}(N) \to \mathbb{R} \) defined on a set of all possible coalitions (i.e. all possible subsets of \( N \)) that satisfies \( v(\emptyset) = 0 \). Function \( v \) is called the characteristic function of a game. The quantity \( v(S) \) represents the value, power or worth of a coalition \( S \), given that the members of that coalition choose to play together. The above-mentioned condition means that an empty coalition has no value. Sometimes it is also requested that the characteristic function meets the condition of superadditivity, meaning that adding a new member (or several members) to any coalition leads to a value equal or greater than the sum of those two smaller coalitions get when they play separately. Mathematically, this request can be formulated as \( v(S \cup T) \geq v(S) + v(T) \) for any two disjointed sets \( S \) and \( T \) (\( S \cap T = \emptyset \)).

The key question that needs to be answered is, in case a coalition forms, how to divide its joined value among its members. Division should reflect the power of each member, meaning that it should reflect the contribution of each member to the total utility achieved in a coalition. Function that divides the utility among the members of a coalition is called a value function \( \phi \). Given the set of players \( N = \{1, 2, \ldots, n\} \) that form a coalition and a characteristic function \( v \), \( (\phi_1(v), \phi_2(v), \ldots, \phi_n(v)) \) represents the division of value among players, where \( \phi_i(v) \) represents the value that is assigned to player \( i \). There are many possible ways to divide the total utility, but the chosen solution concept should satisfy properties that ensure a fair division. Shapley proposed four axioms that such a function needs to meet (Shapley, 1953). Those axioms came to be known as Shapley’s axioms of fairness (Ferguson, 2014):

1. Efficiency: \( \sum_{i \in N} \phi_i(v) = v(N) \)
2. Symmetry: If \( i \) and \( j \) are such that \( v(S \cup \{i\}) = v(S \cup \{j\}) \) for every coalition \( S \) not containing \( i \) and \( j \), then \( \phi_i(v) = \phi_j(v) \).
3. Dummy axiom: If \( i \) is such that \( v(S \cup \{i\}) = v(S) \) for every coalition \( S \) not containing \( i \), then \( \phi_i(v) = 0 \).
4. Additivity: If \( v \) and \( u \) are characteristic functions, then \( \phi(u + v) = \phi(u) + \phi(v) \).

Efficiency axiom states that value function needs to divide the total value of a coalition among players. Symmetry axiom requires that, if some two players add equal value to every possible coalition that does not contain them, then value function needs to assign equal value to both of them. Dummy axiom requires zero value to be assigned to a player who adds no value to any coalition. Finally, the additivity axiom says that value of two games played separately should be equal to the value when they are played simultaneously.

Shapley (1953) proved that there is only one possible value function \( \phi \) (i.e. only one possible distribution of gained utility) satisfying given axioms. The value that is assigned to players using this allocation is called Shapley value and it can be proved that it is given by represents the cardinality, i.e. the number of elements in a set \( S \), in our case the number of players in a coalition \( S \).
\[
\phi_i(v) = \sum_{S \subseteq N} \frac{(|S|-1)!(n-|S|)!}{n!} \left[ v(S) - v(S, \{i\}) \right]
\]  

Shapley value can be calculated as an average marginal contribution of given player \( i \) to a coalition \( S \) averaged by all possible permutations in which the coalition can be made.

We will be using Shapley value to decompose the risk of a portfolio. The value function \( v \) that we use is in fact the risk measure and it will be denoted by \( \rho \) henceforth.

**Results and discussion**

In order to demonstrate Shapley value application for risk assessment, weekly data on value of five sector indices on Croatian stock exchange (tourism – TUR, food – NUTR, construction – KONS, industry – INDU and transport – TRAN) has been obtained for the period February 21th 2013 until March 15th 2019 (Zagreb Stock Exchange, 2019). The summary statistics for logarithmic returns are presented in the table 1:

**Table 1: Descriptive statistics for observed stock returns.**

<table>
<thead>
<tr>
<th></th>
<th>TURI</th>
<th>NUTR</th>
<th>KONS</th>
<th>INDU</th>
<th>TRAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.0038</td>
<td>-0.0025</td>
<td>-0.0024</td>
<td>-0.0005</td>
<td>-0.0013</td>
</tr>
<tr>
<td>Median</td>
<td>0.0018</td>
<td>-0.0025</td>
<td>-0.0032</td>
<td>0.0002</td>
<td>-0.0032</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.1152</td>
<td>0.0595</td>
<td>0.1550</td>
<td>0.1064</td>
<td>0.1316</td>
</tr>
<tr>
<td>Minimum</td>
<td>-0.0680</td>
<td>-0.1575</td>
<td>-0.3001</td>
<td>-0.1223</td>
<td>-0.1492</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.0216</td>
<td>0.0225</td>
<td>0.0458</td>
<td>0.0268</td>
<td>0.0334</td>
</tr>
<tr>
<td>Jarque Bera</td>
<td>402.59 (0.00)</td>
<td>1882.5 (0.00)</td>
<td>498.79 (0.00)</td>
<td>123.08 (0.00)</td>
<td>66.655 (0.00)</td>
</tr>
</tbody>
</table>

In order to calculate Shapley value decomposition of risk in a portfolio, we need to choose underlying risk measure. As a starting point, we used Markowitz mean-variance model (Markowitz, 1952). The underlying risk measure that we use is variance of global minimum variance portfolio.

Since there are 5 indices that are being used in the analysis, there are \( 2^5 = 32 \) subsets for which we need to determine coalition value. For an empty coalition, we set the risk measure to zero, \( \rho(\emptyset) = 0 \). For each subset \( S \subseteq N \) of assets (sector indices), we calculated vector of means and covariance matrix and using those data constructed global minimum-variance portfolio, i.e. portfolio from an efficient frontier with a minimum variance. The optimal portfolios that are calculated using different assets have unequal expected returns, what makes them incomparable. This means that marginal contribution of an asset to risk of a portfolio can't be calculated by simple subtraction of risk in a portfolio that contains that asset and a portfolio without it. In order to make these variances comparable among different subsets, some transformation of the data needs to be done.

It is natural to request that chosen transformation results in risk measure that assigns greater value for a portfolio with a greater variance, compared to one with a smaller variance and
equal expectation. Similarly, portfolio with a smaller expectation should have a greater risk measure, given equal variance.

Since simple division of standard deviation by mean wouldn't meet these conditions, we instead use a \( 1 - \mu_S \) as a denominator (\( \mu_S \) represents the mean of the global minimum-variance portfolio consisted of assets in \( S \)). Therefore, the risk measure that we use is

\[
\rho(S) = \frac{\sigma_S}{1 - \mu_S},
\]

where \( \sigma_S \) represent the standard deviation of the optimal portfolio constructed from the assets in \( S \), and \( \mu_S \) represents the mean of the same portfolio, as mentioned earlier. Since function \( x \mapsto 1 - x \) is monotonically decreasing, the abovementioned conditions are met.

Using this risk measure as a characteristic function, we calculated Shapley value of each asset using formula (1). The results are presented in a Table 2. Additionally, we calculated normed Shapley value of each asset:

\[
\phi_i(\rho) = \frac{\phi_i(\rho)}{\sum_i \phi_i(\rho)}.
\]

This transformation ensures that the sum of calculated values is equal to 1 what makes it easier to interpret the results. The third row in a table are weights in the global minimum variance portfolio constructed using all assets (the grand coalition).

**Table 2: Shapley value using risk measure \( \rho \)**

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Shapley value</td>
<td>-0.000866</td>
<td>0.000241</td>
<td>0.008767</td>
<td>0.002121</td>
<td>0.004539</td>
</tr>
<tr>
<td>Normed Shapley</td>
<td>-0.0585</td>
<td>0.0163</td>
<td>0.5923</td>
<td>0.1433</td>
<td>0.3067</td>
</tr>
<tr>
<td>Weight in the</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>optimal portfolio</td>
<td>0.3678</td>
<td>0.2910</td>
<td>0.0101</td>
<td>0.2085</td>
<td>0.1227</td>
</tr>
</tbody>
</table>

Figure 3 shows all five indexes in the observed period.

Our procedure assigned negative value to TURI, meaning that, in general, marginal contribution of this asset to risk of a portfolio was negative. This result is in line with weights in the optimal portfolio consisted from all five assets, with previously observed summary statistics and with the graph of index values. Similarly, risk contribution of NUTR is assessed to be 1.63%. This asset is also heavily represented in the optimal portfolio. The biggest discrepancy between these two methods is obtained for INDU sector. Optimal portfolio results suggest investing 21% of portfolio value in this sector, while Shapley value risk measure estimates that around 14% of risk comes from this asset. Such a great weight of INDU in an optimal portfolio can be explained using correlation matrix. Since TURI is an asset that accounts for the largest percentage of the optimal portfolio value and INDU is an asset with weakest correlation to it, including NUTRI in portfolio can be beneficial as a diversification tool. As in case of TURI, results for KONS are also strongly supported by results in the optimal portfolio. According to Shapley value risk decomposition, KONS is
responsible for almost 60% of overall risk. The optimal portfolio invests only around 1% of its value in this asset, what, once again, confirms the adequacy of this procedure for portfolio risk analysis.

Figure 3: Index values in observed period

Table 4: Correlation matrix for index returns

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<tr>
<th></th>
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<th>NUTRI</th>
<th>KONS</th>
<th>INDU</th>
<th>TRANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TURI</td>
<td>1</td>
<td>0.20700105</td>
<td>0.1462891</td>
<td>0.04414171</td>
<td>0.13677373</td>
</tr>
<tr>
<td>NUTRI</td>
<td>0.20700105</td>
<td>1</td>
<td>0.2002607</td>
<td>0.21769169</td>
<td>0.05440403</td>
</tr>
<tr>
<td>KONS</td>
<td>0.1462891</td>
<td>0.20026069</td>
<td>1</td>
<td>0.22924272</td>
<td>0.13774942</td>
</tr>
<tr>
<td>INDU</td>
<td>0.04414171</td>
<td>0.21769169</td>
<td>0.22924272</td>
<td>1</td>
<td>0.16914072</td>
</tr>
<tr>
<td>TRANS</td>
<td>0.13677373</td>
<td>0.05440403</td>
<td>0.13774944</td>
<td>0.16914072</td>
<td>1</td>
</tr>
</tbody>
</table>

Previously described procedure provides Shapley values of each asset represented as single-number measures of risk a particular asset poses for a portfolio. This measure captures not just the volatility of that particular asset, but also the potential risk growth and risk reduction that an asset brings to a portfolio. It averages its marginal risk contribution over all possible portfolios, meaning that it contains all the information of asset interaction with the market. It measures the way the risk of a portfolio reacts when this asset is introduced to that portfolio. Any measure that does not include the information about the way the asset interacts with other assets or a market can be seen only as a partial measure of risk. Since this risk division satisfies Shapley’s fairness axioms, we find risk measures obtained
using Shapley value division to be more complete and also more fair than any risk measure obtained by treating an asset as an isolated object rather than a market component.

Prior to calculation of Shapley value one must first estimate the characteristic function (value of each possible coalition), leading to an exponential growth in the number of problems that need to be solved. Furthermore, complexity of calculation strongly depends on an underlying model or risks measure that is being used. This procedure can be applied on any risk measure, but one must consider the limitations and disadvantages of the chosen measure. We used variance to capture the risk of a portfolio, but the same analysis can be done using another risk measure, for example some downside risk measure. Using such a measure will lead to a Shapley value division that has more desirable properties. An additional problem that occurs is the problem of comparing the risk at different return levels. The cause of this problem is Shapley value, which is a tool developed to divide the utility in a one attribute environment, while portfolio analysis is generally considered to be a problem with two variables of interest—risk and return. The optimal portfolio for a given coalition does not have to have the same expected yield as the optimal portfolio formed from another set of assets (another coalition). This means that either single-index model for portfolio analysis needs to be used or when using two-index model, an optimal solution needs to be adjusted so that the calculated risks of the optimal portfolios are mutually comparable. This creates room for numerous possible variations on transformation function that is used prior to applying Shapley value calculation procedure.

**Conclusion**

Shapley value offers a way to summarize risk of an asset and its possible contribution to risk increase or decrease when entering the portfolio. This is important since it is well known that the volatility of an asset is not the only factor that needs to be considered when choosing whether or not to include that asset in a portfolio. Risk measures that are based solely on information obtained from that asset returns (without regard for other participants in a portfolio or a market) can only be seen as partial risk measure. Shapley value is a tool that can be used to transform these partial risk measures into a more complete measure. This transformation can be done in various ways, creating a room for modifications that will result in a risk measure with desirable characteristics. We propose one possible transformation that can be used. The obtained measure represents a fair division of risk in a portfolio. It is possible that a negative value is assigned to an asset. This means that, on average, this asset reduces the risk of a portfolio when added into it. This is the consequence of taking into account interactions between assets, not just the volatility of an individual, isolated asset. The properties of Shapley value ensure that the risk division estimated in this manner is fair—it assigns risk so that the value assigned to an asset reflects the overall cost of having an asset in a portfolio.

We showed that the results from Croatian Market in proposed setup are in line with what one might expect from a complete risk measure. Since research in this area using Shapley value is still very scarce and the results are promising, this motivates future research with different possible portfolio constructing model or different transformations to achieve comparability. Also, this methodology should be tested using larger data pool from different markets. This can be problematic since the main downside of this method is its complexity—the number of optimization problems that need to be solved prior to computing the Shapley value grow exponentially with the number of assets of interest. Additionally, the methodology could be
expanded for dynamic portfolio construction, but his would also enlarge the complexity of estimation.

References


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